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Novel Calibration of MIESM and Reduction of CQI Feedback for Improved Fast Link Adaptation

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Abstract: In mobile communications systems, fast link adaptation (FLA) aims to achieve high system throughput of each user by accurately determining a channel quality indicator (CQI) for feedback, which predicts the next channel based on the current channel state information. In this paper, we propose an improved calibration method of mutual information effective signal-to-noise-ratio mapping (MIESM) to determine an accurate CQI feedback value in FLA. Our proposed calibration method derives the optimal calibration factors by considering various channel environments and setting the effective interval of effective signal-to-noise ratio, which is a single value compressing the information of channel characteristics at a time. The simulation is performed in various signal-to-noise ratio (SNR) ranges to account for the actual environments, and the calibration factors are derived from the proposed calibration method. The results show that the CQI feedback value from the derived calibration factors are more accurate than the existing calibration factors. In addition, we discuss a study regarding the time-coherence-based CQI feedback bit reduction scheme. Assuming that each channel is correlated to the previous and subsequent channels, we propose a method to reduce the number of CQI feedback bits adapted to the corresponding SNR regime. Through the simulation, we compare the system throughputs of the proposed adaptive CQI feedback and the conventional CQI feedback scheme. As a result, the proposed CQI feedback has almost the same system throughput as the conventional CQI feedback scheme, but the average number of feedback bits is reduced, thereby improving the efficiency of the communication.

Keywords: fast link adaptation (FLA); channel quality indicator (CQI); calibration method; calibration factor; CQI feedback

1. Introduction

In mobile communications systems, the channel experienced by each user is apt to having frequency selectivity and time variation. In this situation, the user selects a channel quality indicator (CQI) by estimating an appropriate link quality for the fading channel through fast link adaptation (FLA) and sends the feedback. The base station (BS) selects a modulation and coding scheme (MCS) for transmission based on the CQI feedback from the user [1,2]. If the channel condition is determined to be good enough, the BS increases the modulation order and/or coding rate. In the opposite case, the BS decreases them. This FLA process with resource allocation increases the throughput of the system while maintaining the quality of service (QoS) between the user and the BS [3–7].

Although the FLA can use various metrics to predict link quality [8–10], in this paper, we use mutual information effective signal-to-noise-ratio mapping (MIESM) [11,12], which is a tool to obtain an accurate link-quality metric (LQM) to determine the CQI value for the instantaneous channel. The MIESM utilizes the instantaneous signal-to-noise ratios (SNRs) of subcarriers to compute the

effective SNR, which is a constant value representing the whole-channel quality. In this process, a calibration factor is used to calculate the effective SNR in the MIESM procedure. The optimal calibration factor enables the most accurate block error rate (BLER) prediction for a given channel, allowing reliable CQI selection.

There were a few research works handling the calibration of MIESM. In Reference [11], the calibration factor of MIESM and its derivation were addressed first, but no detailed calibration procedure was given. In Reference [12], the standard method of calibration was proposed. In Reference [13], the average method was proposed to reduce the complexity during the calibration compared to the standard method. In Reference [14], an approximated version of MIESM was proposed for 256 quadrature amplitude modulation (QAM) in long-term evolution (LTE), but no calibration procedure was required. All the existing calibration methods of MIESM were performed using only limited channel environments without consideration of various channel conditions of mobile communications. This is not an optimal method considering FLA in actual situations.

Accurate CQI estimation of the FLA enables reliable communication with high throughput between the user and the BS [15–17]. The CQI reporting method of the user includes periodic reporting of CQI feedback at regular intervals and aperiodic reporting, which feeds back the CQI according to the request of the BS. There are three types of CQI feedback: wideband, higher layer-configured subband feedback, and UE selected subband CQI feedback [18]. The subband is defined by dividing the entire downlink bandwidth (wideband) by the subband size according to the number of resource blocks. One subband consists of consecutive physical resource blocks (PRBs), and it is the smallest unit for CQI feedback reporting. An efficient CQI feedback reporting reduces the overhead of uplink communication between the user and the BS. The CQI is reported differently depending on the channel state information (CSI) [19]. Differential CQI was adopted to reduce the amount of feedback bits in multi-input multi-output (MIMO) situations of the third generation partnership project (3GPP) evolved universal terrestrial radio access (E-UTRA) [18]. The differential CQI feedback first obtains the wideband CQI from subband CQIs, and then calculates the difference between each subband CQI and the wideband CQI. It is noted that the differential CQI feedback scheme does not utilize channel correlations over time.

In this paper, we propose an improved calibration method for MIESM by deriving the optimal calibration factor to improve the accuracy of CQI feedback in FLA. The improvement of the proposed method comes from two technical advances. Firstly, a wide range of additive white Gaussian noise (AWGN) SNR values are considered in the calibration procedure to reflect various channel conditions of users in reality. Secondly, the proposed method sets an effective interval of the effective SNR to screen unnecessary channels which do not help the calibration eventually. To verify the proposed method, we propose an efficient algorithm to check the accuracy of CQIs calculated from the derived calibration factors. As a result, it was confirmed via the system throughput simulation that the calibration factors derived from the proposed method provide more accurate CQI values than the conventional ones. In addition, under the assumption that there is some correlation in time channels, we also propose a CQI feedback bit reduction scheme which is applicable no matter which scheme is used, i.e., wideband CQI or subband CQI. Based on the time correlation between adjacent channels, the CQI difference of two consecutive channels is mostly bounded, which enables reducing the number of bits used for CQI feedback. Although a reduced number of feedback bits are used, it is shown via simulations that the decrease of the system throughput is negligible, which proves that the proposed CQI feedback bit reduction scheme is efficient and also robust in various channel conditions.

The remainder of the paper is organized as follows: Section 2 explains MIESM-based FLA and the average calibration method. Section 3 presents the improved calibration method to obtain optimal calibration factors. Section 4 introduces the CQI feedback bit reduction schemes. Results of the simulations and the analysis are shown in Section 5. Finally, this paper is concluded in Section 6.

2. Preliminaries

This section describes the MIESM-based FLA mechanism, and introduces the existing calibration method.

2.1. MIESM-Based Fast Link Adaptation

A user obtains the channel coefficient information from the orthogonal frequency division multiplexing (OFDM) symbols, determines a CQI suitable for the current channel through the MIESM-based FLA, and reports it to the BS. The goal of the FLA is to increase the throughput of the system while maintaining the target BLER for various channel conditions. The MIESM-based FLA process is described below [20].

Firstly, the effective SNR (SNR_{eff}), which is a constant representing the channel quality, is calculated from the instantaneous SNRs of the subcarriers based on the estimated values of the channel state information. The equation for this is given in Reference [11] as follows:

$$\text{SNR}_{\text{eff}} = f_m^{-1}\left(\frac{1}{P} \sum_{p=1}^P f_m\left(\frac{\text{SNR}_p}{\beta}\right)\right), \quad (1)$$

where P indicates the number of subcarriers, SNR_p is the instantaneous SNR of the p -th subcarrier, and β is a calibration factor to minimize the difference between the estimated effective BLER (BLER_{eff}) and the real BLER for the current channel in the calibration procedure. The function $f_m(\cdot)$ is the bit-interleaved coded modulation (BICM) capacity curve which depends on the modulation order m . This capacity is equivalent to the mutual information between channel input and output, which is the reason this process is called MIESM [21].

Secondly, the calculated SNR_{eff} is mapped through the pre-calculated AWGN/BLER look-up table (LUT) to the BLER_{eff} value for each CQI. The AWGN/BLER LUT contains all the BLER information of every CQI under the AWGN channel over various SNR values. Then, we select the largest CQI such that the corresponding BLER_{eff} does not exceed the target BLER, which was set to 0.1 in this paper, and feeds the selected CQI back to the BS.

2.2. Average Method for Calibration of MIESM

Accurate CQI determination is possible using appropriate calibration factors for effective SNR calculation. The standard calibration procedure was proposed in Reference [12], which requires a vast number of link-level simulations to include a significant number of channel instances. For this reason, in many cases, the optimal calibration factors are practically obtained from the average calibration procedure outlined in Reference [13].

Before describing the calibration procedure, we explain some notations. These notations are also used for the improved calibration method described in Section 3. N_b is the number of candidate calibration factors for every CQI, and $\beta_{i,l}$, $l = 1, \dots, N_b$, is the l -th calibration factor for CQI i . N_s is the length of AWGN SNR vectors to simulate in search of the optimal calibration factor, where the noise variance corresponding to each SNR is $[\sigma_1^2, \dots, \sigma_{N_s}^2]$. The symbol N_c is the number of channel realizations which should be big enough to show the characteristics of the entire channel, and H_k , $k = 1, \dots, N_c$ is the k -th channel instance. N_w is the number of noise realizations and w_n , $n = 1, \dots, N_w$, is the n -th noise instance. Also, $\text{BLER}_{\text{LUT}}(\text{SNR}_{\text{eff}}(\cdot, \cdot, \cdot))$ is the effective BLER obtained by mapping the SNR_{eff} using the AWGN/BLER LUT.

The calibration steps in Algorithm 1 are further described below. N_c channels and N_w noises are generated for one calibration factor candidate and one AWGN SNR point. The instantaneous $\text{BLER}(H_k, w_n)$ is calculated for the generated channel and noise by decoding. This value is 0 if the block is correct, or 1 otherwise. The average BLER ($\text{BLER}(H_k, \sigma_j^2)$) over noise is then calculated and accumulated. Then, the average BLER ($\overline{\text{BLER}}(\sigma_j^2)$) over a given channel and noise realization

is calculated and saved. The BLER_{LUT} is estimated using SNR_{eff} , and this is also averaged over the entire channel.

Algorithm 1 Average calibration method

Input: CQI index i ($i = 1, 2, \dots, 15$)
 $B_i = \{\beta_{i,1}, \beta_{i,2}, \dots, \beta_{i,N_b}\}$

Output: $\hat{\beta}_i$

```

1:   for  $l = 1$  to  $N_b$  (for all candidates in  $B_i$ ) do
2:     for  $j = 1$  to  $N_s$  (for all AWGN SNRs) do
3:        $b = 0$ 
4:       Calculate noise variance:  $\sigma_j^2$ 
5:       for  $k = 1$  to  $N_c$  (for all channel realizations) do
6:         Generate channel:  $H_k$ 
7:          $a = 0$ 
8:         for  $n = 1$  to  $N_w$  (for all noise realizations) do
9:           Generate additive noise:  $w_n$ 
10:          Calculate real BLER from decoding:  $\text{bler}(H_k, w_n)$ 
11:          Accumulate:  $a = a + \text{bler}(H_k, w_n)$ 
12:        end for
13:        Calculate average (over noise) BLER:
14:         $\text{BLER}(H_k, \sigma_j^2) = a/N_w = \frac{1}{N_w} \sum_{n=1}^{N_w} \text{bler}(H_k, w_n)$ 
15:        Accumulate average BLER:  $b = b + \text{BLER}(H_k, \sigma_j^2)$ 
16:      end for
17:      Calculate and save the average (over noise and channel) BLER:
18:       $\overline{\text{BLER}}(\sigma_j^2) = b/N_c = \frac{1}{N_c} \sum_{k=1}^{N_c} \text{bler}(H_k, \sigma_j^2)$ 
19:    end for
20:    Calculate and save the effective BLER for the current AWGN SNR:
21:     $\overline{\text{BLER}}_{\text{LUT}}(\sigma_j^2, \beta_{i,l}) = \frac{1}{N_c} \sum_{k=1}^{N_c} \text{BLER}_{\text{LUT}}(\text{SNR}_{\text{eff}}(H_k, \sigma_j^2, \beta_{i,l}))$ 
22:  end for
23:   $\hat{\beta}_i = \arg \min_{\beta_{i,l} \in B_i} \sum_{j=1}^{N_s} \varepsilon(\overline{\text{BLER}}(\sigma_j^2), \overline{\text{BLER}}_{\text{LUT}}(\sigma_j^2, \beta_{i,l}))$ 

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The purpose of the calibration is to predict the $\overline{\text{BLER}}_{\text{LUT}}$ as close as possible to the real average $\overline{\text{BLER}}$ for all AWGN SNR values and channel conditions. For this, the above calibration procedure is necessary, and the optimal calibration factor is calculated as

$$\beta_{\text{opt}}^{\text{av}} = \hat{\beta}_i = \arg \min_{\beta_{i,l} \in B_i} \sum_{j=1}^{N_s} \varepsilon(\overline{\text{BLER}}(\sigma_j^2), \overline{\text{BLER}}_{\text{LUT}}(\sigma_j^2, \beta_{i,l})), \quad (2)$$

where $\varepsilon(x, y)$ is an error function that calculates the error by assigning equal weights to x and y .

$$\varepsilon(x, y) = |\log_{10}(x) - \log_{10}(y)|^2. \quad (3)$$

In general, the AWGN SNR range of the average calibration procedure is limited to SNR points of AWGN/BLER 0.95 to BLER 0.01 for each CQI, since all data collected in the link-level simulation are not sufficiently reliable [13].

3. Improved Calibration Method

The existing calibration method has a limitation, whereby only the limited channel quality is considered because the calibration factor is derived by generating noise for the limited range of AWGN SNR corresponding to the BLER 0.95 to BLER 0.01 in order to find the optimum calibration factors.

The purpose of the improved calibration method is to derive an optimal calibration factor for accurate CQI determination using various channels from a wide SNR range. The following two steps are required before applying the improved calibration method:

- The effective interval of the SNR_{eff} for correctness and efficiency of the calibration must be defined before deriving the calibration factor. Since the CQI feedback value is determined on the basis of the target BLER 0.1, the effective interval of SNR_{eff} is defined from the SNR value corresponding to AWGN BLER 0.9, which is denoted by $\gamma_{0.9}^i$, to the SNR value corresponding to AWGN BLER 0.001, which is denoted by $\gamma_{0.001}^i$, for each CQI. The effective interval efficiently includes valid channels for the calibration around the SNR corresponding to AWGN BLER 0.1.
- The probability distribution of SNR_{eff} over a number of channels must be obtained for each given AWGN SNR and each CQI. The distribution of SNR_{eff} for each AWGN SNR almost follows the Gaussian distribution as shown in Figure 1. Let $\text{SNR}_{\text{eff}}^s$ denote the random variable corresponding to the effective SNR for a given AWGN SNR s when channel coefficients are considered as random. Then, we set the range of AWGN SNR s for calibration such that $P(\gamma_{0.9}^i \leq \text{SNR}_{\text{eff}}^s \leq \gamma_{0.001}^i) \geq 0.05$. Then, let SNR_{min} and SNR_{max} denote the minimum and maximum values of s , respectively. In addition, the probability $P(\gamma_{0.9}^i \leq \text{SNR}_{\text{eff}}^s \leq \gamma_{0.001}^i)$ from the distribution of each SNR is used as a weight to calculate the total error for the optimal calibration factor.

Figure 1. Selecting the additive white Gaussian noise (AWGN) signal-to-noise ratio (SNR) range from the probability density function (p.d.f) for the improved calibration procedure.

The process for deriving the optimal calibration factor is shown below in Algorithm 2.

Algorithm 2 Improved calibration method

Input:	CQI index i ($i = 1, 2, \dots, 15$) $B_i = \{\beta_{i,1}, \beta_{i,2}, \dots, \beta_{i,N_b}\}$
Output:	$\hat{\beta}_i$

```

1:   for  $l = 1$  to  $N_b$  (for all candidates in  $B_i$ ) do
2:     for  $j = 1$  to  $N_s$  (for all SNRs from  $\text{SNR}_{\text{min}}$  to  $\text{SNR}_{\text{max}}$ ) do
3:        $k = 1$ 
4:        $a = 0$ 
5:       Calculate noise variance:  $\sigma_j^2$ 
6:       while  $k \leq N_c$  (for all channel realizations) do
7:         Generate channel:  $H_k$ 
8:          $\text{err}_{\text{cnt}} = 0$ 
9:         Consider only the channels in the effective interval:
10:        if  $\gamma_{0.9}^i \leq \text{SNR}_{\text{eff}}(H_k, \sigma_j^2, \beta_{i,l}) \leq \gamma_{0.001}^i$  do
11:          for  $n = 1$  to  $N_w$  (for all noise realizations) do
            Generate additive noise:  $w_n$ 

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Algorithm 2 *Cont.*

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12:           Count block error:  $err_{cnt} = err_{cnt} + 1$ 
13:       end for
14:        $BLER_{real}(H_k, w_n) = err_{cnt} / N_w$ 
15:        $BLER_{eff}(H_k, \sigma_j^2, \beta_{i,l}) = BLER_{LUT}(SNR_{eff}(H_k, \sigma_j^2, \beta_{i,l}))$ 
16:        $k = k + 1$ 
17:   end if
18:       Accumulate difference between  $BLER_{real}$  and  $BLER_{eff}$ :
19:        $a = a + \varepsilon(BLER_{real}(H_k, w_n), BLER_{eff}(H_k, \sigma_j^2, \beta_l))$ 
20:   end while
21: end for
22: end for
23:  $\hat{\beta}_i = \arg \min_{\beta_{i,l} \in B_i} \sum_{j=1}^{N_s} \{P(\gamma_{0.9}^i \leq SNR_{eff}^{s_j} \leq \gamma_{0.001}^i) \times a\}$ 

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To derive the calibration factor corresponding to each CQI, N_b candidates are specified for the calibration factor. In order to derive a calibration factor suitable for a wide range of AWGN SNR, the SNR vector of the proposed method takes the range corresponding to effective SNR (SNR_{eff}) of 5% or more obtained from the preliminary simulation, where N_s is the total number of SNR values to simulate. The N_c channels are generated according to the channel model. Then, noise is generated if the effective SNR is included in the effective interval for the generated channel, and the errors are counted (err_{cnt}). The variable err_{cnt} accumulates the number of block errors. It is used to calculate the real BLER ($BLER_{real}$) of a physical layer for a given channel and noise. The estimated BLER ($BLER_{eff}$) is calculated using the pre-calculated SNR_{eff} , and the error between the $BLER_{real}$ and $BLER_{eff}$ is accumulated for all the channels. The error function of Equation (3) is again used for the error calculation. The accumulated errors are multiplied by the distribution of SNR_{eff} corresponding to each SNR as the weight. The β_l with the smallest sum of these is determined as the optimum value of the calibration factor. The related expression is shown in Equation (4).

$$\beta_{opt}^{improv} = \hat{\beta}_i = \arg \min_{\beta_{i,l} \in B_i} \sum_{j=1}^{N_s} \{P(\gamma_{0.9}^i \leq SNR_{eff}^{s_j} \leq \gamma_{0.001}^i) \times \sum_{k=1}^{N_c} \varepsilon(BLER_{real}, BLER_{eff})\}. \quad (4)$$

The complexity of a calibration method mostly depends on the number of decoding trials at the physical layer. The proposed calibration method has the exact same number of decoding trials as the average method when parameters are identically set. Specifically, the number of decoding trials for both calibration methods is $N_b N_s N_c N_w$. Therefore, it can be said that the improved calibration method does not require more computational complexity than the average method.

4. Reduction of CQI Feedback Bits

This section discusses schemes for reducing wideband CQI feedback bits. To date, the conventional differential CQI scheme was applied only to wideband CQI feedback. The proposed scheme also uses the difference of CQIs as the conventional method; however, the difference is not between the average CQI and each CQI, but between adjacent time channels under the assumption of the existence of time correlation in channels. The proposed scheme can be applied no matter which one is considered, i.e., wideband CQI or subband CQI. From this, the number of bits used for CQI feedback is reduced. As in LTE, we assume that CQI takes a value from 0 to 15, and each user sends the 4-bit feedback to BS in the conventional scheme. The detailed description of the proposed scheme is shown below in Algorithm 3.

Algorithm 3 The 1-bit reduction scheme of CQI feedback at each user

Input:	$CQI_{k-1} \rightarrow$ Integer value of CQI feedback value for the $(k-1)$ -th subframe
Output:	$FB_k \rightarrow$ 1-bit reduced binary vector to feedback for the k -th subframe
1:	Determine CQI from the FLA in Section 2 for the current channel, denoted by $\overline{CQI}_k$
2:	Compute the difference of consecutive CQI feedback values: $\overline{CQI}_k^{\text{diff}} = \overline{CQI}_k - CQI_{k-1}$
3:	Determine CQI_k^{diff} such that if $CQI_{k-1} \leq 4$ and $\overline{CQI}_k^{\text{diff}} \geq 8 - CQI_{k-1} \Rightarrow CQI_k^{\text{diff}} = 7 - CQI_{k-1}$ elseif $CQI_{k-1} \geq 12$ and $\overline{CQI}_k^{\text{diff}} \leq 7 - CQI_{k-1} \Rightarrow CQI_k^{\text{diff}} = 8 - CQI_{k-1}$ elseif $5 \leq CQI_{k-1} \leq 11$ and $\overline{CQI}_k^{\text{diff}} \geq 4 \Rightarrow CQI_k^{\text{diff}} = 3$ elseif $5 \leq CQI_{k-1} \leq 11$ and $\overline{CQI}_k^{\text{diff}} \leq -5 \Rightarrow CQI_k^{\text{diff}} = 3$ else $CQI_k^{\text{diff}} = \overline{CQI}_k^{\text{diff}}$
4:	$FB_k = \text{decimal_to_binary}(CQI_k^{\text{diff}} \bmod 8)$
5:	Send the feedback FB_k to BS

Firstly, we calculate the difference $\overline{CQI}_k^{\text{diff}}$ between $\overline{CQI}_k$ which is the CQI temporarily determined in a normal way for the current channel, and CQI_{k-1} which is the CQI the BS used for the MCS of the previous channel. The calculated $\overline{CQI}_k^{\text{diff}}$ is used to determine the integer value of CQI_k^{diff} which is sent to the BS after being converted into a binary form FB_k . A detailed description of the above process is shown in Figure 2.

Figure 2. Examples for the process of the 1-bit reduction scheme of channel quality indicator (CQI) feedback.

The proposed scheme reduces the number of bits used for CQI feedback by 1 bit and expresses eight CQI indexes with 3 bits in total. Figure 2 shows an example of the CQI feedback range that can be represented by 3 bits according to CQI_{k-1} . Otherwise, the $\overline{\text{CQI}}_k$ is changed to the CQI closest to the range; then, the bit value of the CQI is fed back. In most cases, the range is specified as $(\text{CQI}_{k-1} - 4)$ to $(\text{CQI}_{k-1} + 3)$ based on CQI_{k-1} . The above interval was determined by observing the CQI difference of one million subframes of each SNR. If CQI_{k-1} is low or high, it is impossible to use the above definition of interval. Therefore, an adaptive interval setting is necessary, and the relevant examples correspond to Figure 2b,c.

The BS uses the FB_k fed back from the user and performs the recovery algorithm for the actual CQI, as shown in Algorithm 4. Then, it determines resource assignment, MCS, and transport block size (TBS) suitable for the current channel according to the CQI_k and transmits the data.

Algorithm 4 CQI recovery at BS from 1-bit reduced feedback

Input: $\text{FB}_k \rightarrow$ 1-bit reduced binary vector received from the user for the k -th subframe
Output: $\text{CQI}_k \rightarrow$ CQI value of the k -th subframe to be used in BS

1: $\overline{\text{CQI}}_k^{\text{diff}} = \text{binary_to_decimal}(\text{FB}_k)$
2: Recover $\text{CQI}_k^{\text{diff}}$
 if $(\text{CQI}_{k-1} \leq 3 \text{ and } \overline{\text{CQI}}_k^{\text{diff}} \geq 8 - \text{CQI}_{k-1})$ or
 $(\text{CQI}_{k-1} \geq 13 \text{ and } \overline{\text{CQI}}_k^{\text{diff}} \geq 16 - \text{CQI}_{k-1})$ or
 $(4 \leq \text{CQI}_{k-1} \leq 12 \text{ and } \overline{\text{CQI}}_k^{\text{diff}} \geq 4)$
 then, $\text{CQI}_k^{\text{diff}} = \overline{\text{CQI}}_k^{\text{diff}} - 8$
 else $\text{CQI}_k^{\text{diff}} = \overline{\text{CQI}}_k^{\text{diff}}$
3: Calculate CQI_k from $\text{CQI}_k^{\text{diff}}$
 $\text{CQI}_k = \text{CQI}_{k-1} + \text{CQI}_k^{\text{diff}}$

In a low-SNR environment of fading channels, we observe that the change in CQI values of adjacent channels is not large compared to high-SNR cases. In this situation, CQIs of a small level (i.e., CQI 0, CQI 1, and CQI 2) are frequently generated. We can use this observation to further reduce the bits used for CQI feedback. When the feedback CQI value for the previous channel is $\text{CQI}_{k-1} = 0, 1, 2$, we bound the CQI difference between consecutive channels as -2 to 1 , which results in 2-bit feedback for the current channel. The 2-bit CQI feedback representation method for CQIs 0, 1, and 2 is shown in Algorithm 5, and it is noted that the recovery at BS is easily described in the same way with Algorithm 4.

Algorithm 5 The 1- or 2-bit reduction scheme of CQI feedback at each user

Input: $\text{CQI}_{k-1} \rightarrow$ Integer value of CQI feedback value for the $(k-1)$ -th subframe
Output: $\text{FB}_k \rightarrow$ 1 or 2-bit reduced binary vector to feedback for the k -th subframe

1: Follow the Steps 1 and 2 in Algorithm 3
Determine $\text{CQI}_k^{\text{diff}}$ and formulate FB_k for $\text{CQI}_{k-1} = 0, 1$, or 2 such that
2: if $0 \leq \text{CQI}_{k-1} \leq 2$ and $\overline{\text{CQI}}_k^{\text{diff}} \geq 4 - \text{CQI}_{k-1} \Rightarrow \text{CQI}_k^{\text{diff}} = 3 - \text{CQI}_{k-1}$
 $\text{FB}_k = \text{decimal_to_binary}(\text{CQI}_k^{\text{diff}} \bmod 4)$
Determine $\text{CQI}_k^{\text{diff}}$ and formulate FB_k for the other cases such that
3: if $3 \leq \text{CQI}_{k-1} \leq 4$ and $\overline{\text{CQI}}_k^{\text{diff}} \geq 8 - \text{CQI}_{k-1} \Rightarrow \text{CQI}_k^{\text{diff}} = 7 - \text{CQI}_{k-1}$
elseif $\text{CQI}_{k-1} \geq 12$ and $\overline{\text{CQI}}_k^{\text{diff}} \leq 7 - \text{CQI}_{k-1} \Rightarrow \text{CQI}_k^{\text{diff}} = 8 - \text{CQI}_{k-1}$
elseif $5 \leq \text{CQI}_{k-1} \leq 11$ and $\overline{\text{CQI}}_k^{\text{diff}} \geq 4 \Rightarrow \text{CQI}_k^{\text{diff}} = 3$
elseif $5 \leq \text{CQI}_{k-1} \leq 11$ and $\overline{\text{CQI}}_k^{\text{diff}} \leq -5 \Rightarrow \text{CQI}_k^{\text{diff}} = 3$
else $\text{CQI}_k^{\text{diff}} = \overline{\text{CQI}}_k^{\text{diff}}$
 $\text{FB}_k = \text{decimal_to_binary}(\text{CQI}_k^{\text{diff}} \bmod 8)$
4: Send the feedback FB_k to BS

The proposed CQI feedback schemes firstly use the conventional CQI calculation. Then, they perform some comparison operations and simple substitution or subtraction based on the calculated CQI value. The computational complexity of the following operations is negligible compared to the first CQI calculation. Therefore, it can be said that the proposed CQI feedback schemes have almost the same computational complexity as the conventional CQI feedback scheme.

5. Simulation Results

In this section, we introduce the verification algorithm for evaluating the performance of the newly derived calibration factors. Also, we verify the performance of the proposed method in Sections 3 and 4 through system throughput simulations.

5.1. Verification Algorithm for FLA

The simulation was performed at the intermediate SNR of the interval where the SNR_{eff} distribution ratio of each CQI was 5% or more. The information bits were encoded according to the modulation order and coding rate corresponding to 15 CQIs, and were passed through the generated channel and noise. We decoded the received data and calculated $\text{BLER}_{\text{real}}$ s for all CQIs from the link-level simulation for a given channel and noise. Then, we determined a final CQI (CQI_{real}) by selecting the largest CQI index such that it satisfied the condition of the target BLER among the $\text{BLER}_{\text{real}}$ corresponding to each CQI. At the same time, SNR_{eff} corresponding to the current channel was calculated, and the effective CQI (CQI_{eff}) was determined by calculation. If the CQI_{real} and CQI_{eff} were the same, the link quality was considered correct; then, verification proceeded to the next channel. Otherwise, the number of errors was increased by one before verification proceeded to the next channel.

5.2. Performance Evaluation

The following simulations were performed in a single-user (SU) single-input single-output (SISO) environment. It can be noted that all the proposed schemes in this paper can also be applied to MIMO systems, but the superiority of the proposed scheme over conventional ones can be sufficiently shown through just SISO simulations.

5.2.1. Improved Calibration Method

We present CQI feedback error rate and system throughput as measures for performance evaluation of the proposed calibration method. The common simulation parameters for evaluating the performance of the proposed calibration factors in this paper are presented in Table 1.

Table 1. Common simulation parameters for performance evaluation. SUSISO—single-user single-input single-output.

Parameter	Value
Simulation type	SUSISO
Bandwidth	1.4 MHz
Carrier frequency	2.0 GHz
Subcarrier spacing	15 kHz
Cyclic prefix	Normal CP
Channel estimation	Perfect
Channel model	VehA
Number of PDCCH	3
Velocity	30 km/h
Receiver	Zero forcing

- Comparison of CQI Feedback Error Rates

In order to guarantee the reliability of the verification, 5000–10,000 channels were generated until the feedback error count exceeded 100 in each SNR. Noise occurred a maximum of 2000 times until the accumulated number of subframe transmission failures reached 100. Figure 3 shows the CQI feedback error rates for the calibration factors of the existing average calibration method and the calibration factors derived from the improved calibration method. Based on the verification algorithm in Section 5.1, the CQI feedback error rate was calculated by counting the number of times that the CQI_{real} determined by the $BLER_{real}$ from the physical layer simulation was not equal to the CQI_{eff} determined by SNR_{eff} .

Figure 3. Comparison of CQI feedback error rates for the calibration factors derived from the average calibration method and the improved calibration method.

In the case of $SNR = -2$ dB, the CQI feedback error rate of the proposed method was larger than that of the conventional method by 10.31%, and for $SNR = 8$ and 22 dB, the CQI feedback error rates of the proposed method were lower than those of the conventional method by 20.38% and 48.78%, respectively. Based on Figure 3, the calibration factors derived from the proposed method show smaller CQI feedback error rates than the conventional method for all SNR values >2 dB, but they show similar to or slightly larger rates than those of the conventional method for $SNR \leq 2$ dB. This result in low-SNR environments is due to the BLER curve slope of the AWGN channel. In the proposed method, we set the SNR corresponding to BLER 0.9 and 0.001 of each CQI as the effective interval of the effective SNR, and derived the calibration factor using the more valid channel for CQI feedback; however, the calibration factor of the existing method was derived without setting it separately. For small CQI values that occur frequently in the low-SNR range, the BLER curve of the AWGN channel is relatively flat, such that the calibration factor can be calculated by sufficiently including the valid channel near the target BLER with the conventional calibration method. On the other hand, since the BLER curve of the AWGN channel is steep for a large CQI, the conventional method calculates the calibration factor without including the valid channel well. However, the proposed calibration method shows better performance than the conventional method because the effective interval works successfully.

- Comparison of System Throughputs

The system throughput was calculated by applying calibration factors derived from the average calibration method and the improved calibration method to the actual mobile communication environment. The simulation was performed over a wide SNR interval, and the system throughput for each method is shown in Table 2.

Table 2. System throughput comparison of the improved calibration method and the average calibration methods (Mbps). SNR—signal-to-noise ratio.

Calibration Method \ SNR (dB)	SNR (dB)						
	−10	−7	−4	−1	2	5	8
improved	0.014636	0.056152	0.140616	0.286313	0.498090	0.783961	1.150098
average	0.014707	0.056163	0.140429	0.285541	0.497030	0.782343	1.148416

Calibration Method \ SNR (dB)	SNR (dB)						
	11	14	17	20	23	26	29
improved	1.592679	2.113780	2.675177	3.180670	3.551829	3.781508	3.904715
average	1.590840	2.110598	2.666004	3.173200	3.545650	3.775832	3.900796

The calibration factor obtained using the average method at $\text{SNR} \leq -7$ dB had a maximum system throughput of 0.07 kbps higher than the proposed method. As described above, in an environment in which a low CQI is frequently fed back, the proposed method does not show better performance because the effective interval is not used efficiently. However, in the remaining SNR ranges, the proposed calibration method achieved high system throughput performance of at least 0.18 kbps and up to 9.17 kbps.

5.2.2. Reduction of CQI Feedback Bits

Through this experiment, the system throughput of the conventional CQI feedback method and the time-coherence-based CQI feedback method were compared. The simulation set-up is listed in Table 3.

Table 3. Simulation parameters for system throughput of the proposed channel quality indicator (CQI) feedback scheme.

Parameter	Value
Simulation type	SUSISO
Bandwidth	1.4 MHz
Carrier frequency	2.0 GHz
Subcarrier spacing	15 kHz
Cyclic prefix	Normal CP
Channel estimation	Perfect
Channel model	VehA
Velocity	30 km/h
Receiver	Zero forcing
Number of subframes	100,000
CQI feedback period time	1 ms

Table 4 shows the system throughput according to the existing 4-bit wideband CQI feedback report in various SNR environments, and Table 5 shows the difference in system throughput between the existing method and the proposed method. In addition, all the system throughputs and the difference for each SNR are shown in Figure 4.

Table 4. System throughput of the 4-bit wideband CQI feedback (Mbps).

SNR (dB)	−10	−7	−4	−1	2	5	8
Throughput	0.0146321	0.0560517	0.1404964	0.2860831	0.4981283	0.7843385	1.1504057

SNR (dB)	11	14	17	20	23	26	29
Throughput	1.5927229	2.1139200	2.6759019	3.1811068	3.5524640	3.7814499	3.9047303

Table 5. System throughput differences between the existing and the proposed CQI feedback schemes (kbps).

SNR (dB)	−10	−7	−4	−1	2	5	8
Scheme							
PROP_3bit	0	0	0	0	0	−0.0006399	0.0266000
PROP_2,3bit	0	0.0033000	0.1060000	0.7003000	1.3095000	1.2034000	0.7957000
SNR (dB)	11	14	17	20	23	26	29
Scheme							
PROP_3bit	−0.4101000	0.2572000	0.6247000	−0.3819000	0.4075000	0.6084000	0.2507000
PROP_2,3bit	0.1600000	0.2782000	0.6247000	−0.3819000	0.4075000	0.6084000	0.2507000

Figure 4. Comparison of system throughputs for CQI feedback schemes.

In the legend of Figure 4, “Existing” represents the conventional CQI feedback scheme in LTE, “PROP-3bit” represents the 1-bit reduced CQI feedback scheme proposed in Algorithm 3, and “PROP-2,3bit” represents the 1- or 2-bit reduced CQI feedback scheme proposed in Algorithm 5. In some SNR environments, the system throughput of existing CQI feedback schemes was slightly higher than that of the proposed scheme. However, the system throughput of the proposed technique was higher at some SNR points (5, 11, and 20 dB). Because of the limited range of CQI variation, the proposed method often provided more stable CQI feedback for the next channel than the conventional method. Though the proposed scheme uses limited CQI index representation for bit reduction, the above simulation results show that the system throughput difference is negligible.

Table 6 shows the average number of bits of PROP_2,3bit used for CQI feedback according to the SNR environment. From the results in Figure 4 and Tables 5 and 6, we can observe that, in low-SNR environments, only 2 bits are sufficient for CQI feedback.

Table 6. Average number of feedback bits of the 1- or 2-bit reduced CQI feedback scheme (bits).

SNR (dB)	−10	−7	−4	−1	2	5	8
Average bits used	2.0011	2.0426	2.2593	2.5995	2.8491	2.9586	2.9922
SNR (dB)	11	14	17	20	23	26	29
Average bits used	2.9991	2.9999	3	3	3	3	3

6. Conclusions

In this paper, we proposed an improved calibration factor derivation method for accurate link-quality determination of mobile communications in various channel environments, and we also suggested a CQI feedback bit reduction scheme for reporting downlink channel state information to BS. The improved calibration method sets the effective interval for the effective SNR to derive the optimal calibration factor used by the MIESM using more valid channels in a wide SNR range. The CQI feedback bit reduction scheme applies a differential CQI technique based on the time correlation between adjacent channels, which change over time, and decreases the number of bits used for CQI feedback.

The two proposed methods were evaluated and analyzed through simulation. Firstly, the calibration factor derived from the improved calibration method reduced the CQI feedback error rate by 48.8% over the existing calibration factor in the range of SNR >2 dB. Also, the system throughput of proposed scheme was a maximum of 9.17 dB higher than that of the conventional scheme at SNR ≥ -7 dB. This means that, by setting the effective interval in the wide SNR range, the newly derived calibration factor performs better than the existing one. Next, using a reduction of the CQI feedback scheme can be used to transmit uplink scheduling information by a reduced number of bits, though the system throughput is almost the same or a maximum of 1.3 kbps lower than the conventional single 4-bit wideband CQI feedback.

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