# Review of Channel Quality Indicator Estimation Schemes for Multi-User MIMO in 3GPP LTE/LTE-A Systems

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## Abstract

Multiple-in multiple-out (MIMO) in long-term evolution (LTE) is an essential factor in achieving high speed data rates and spectral efficiency. The unexpected growth in data rate demand has pushed researchers to extend the benefits of multi-user MIMO. The multi-user MIMO system can take full advantage of channel conditions by employing efficient adjustment techniques for scheduling, and by assigning different modulation and coding rates. However, one of the critical issues affecting this feature is the appropriate estimation of channel quality indicator (CQI) to manage the allocated resources to users. Therefore, an accurate CQI estimation scheme is required for the multi-user MIMO transmission to obtain significant improvements on spectral efficiency. This paper presents overviews of multi-user MIMO in LTE/LTE-advanced systems. The link adaptation, scheduling process, and different factors that affect the reliability of CQI measurements are discussed. State-of-the-art schemes for the post-processing CQI estimation, and the comparisons of various CQI estimation schemes to support multi-user MIMO are also addressed.

***Keywords:*** 3GPP LTE/LTE-A, multi-user MIMO, CQI Estimation, Link Adaptation (LA), Scheduling

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## 1. Introduction

The data traffic of mobile communications devices from around the world has been expanding rapidly, recording a 66-fold increase between 2008 and 2013 [1]. This unpredicted increase in heterogeneous devices has pushed researchers to develop additional advanced features to accommodate enormous data traffic. Thus, long-term evolution (LTE) has been standardized by the Third-Generation Partnership Project (3GPP) as a new access technology to meet the tremendous requirements of current mobile systems. To support the network infrastructure and satisfy the requirements drawn from the International Mobile Telecommunications Advanced, LTE-advanced (LTE-A) has been introduced as a fourth generation (4G) cellular system that is fully endorsed by the Radio communication Sector of the International Telecommunication Union (ITU-R) [2].

Multiple-in multiple-out (MIMO) is a technique that provides significant improvements in data rate, data coverage, and spectral efficiency without increasing power transmission or frequency bandwidth [3]. Although many studies have been conducted to satisfy the diverse sets of requirements, advanced features are still insufficient to meet the growing demand. A multi-user MIMO transmission system is employed as a key enabling transmission technique that simultaneously serves multiple users with the same time and frequency resources. Hence, this technique allows the efficient use of available spectra. The multi-user MIMO system can increase the spectral efficiency by taking the advantages of the channel state into consideration [4], [5]. From a practical implementation perspective, multi-user MIMO system highly depends on the accuracy of channel quality indication (CQI). Failure to estimate the CQI will yield the wrong assignment of radio resources during the scheduling process, incorrect link adaptation decisions, and severe multiuser interference (MUI), which will lead to serious performance degradation [6]. Therefore, optimizing the CQI estimation with a precise method is one of the most important research avenues for supporting multi-user MIMO transmission in LTE/LTE-A systems.

Several methods have been proposed to support CQI estimation. For example, the authors in [7] presented a CQI estimation method that accounts for the interference and quantization errors of multi-user transmission in CQI. This method is assisted by a zero-forcing beam-forming transceiver technique to ignore interference. Methods in [8], [9] were introduced to estimate the signal-to-interference plus noise ratio (SINR). In these methods, SINR is approximated at the receiver side, and CQI value is quantized and reported to the serving evolved node B (eNodeB). Therefore, the reliability of the link adaptation decision is mainly dependent on the reliability of CQI estimation, which is denoted by the post-processed signal at the receiver side. For multi-user MIMO systems with multiple antennas and limited feedback, the authors in [10] introduced a new method called maximum expected SINR combiner, which maximizes the expected SINR. This method is based on a joint optimization design for combining the receiver implementation and quantization of CQI values. The authors in [11] proposed a new scheme of CQI estimation for multi-user MIMO from single-user MIMO systems by generating a lookup table. The optimization lookup table was addressed in [12] by using an adaptive fixed offset method for estimating CQI in multi-user MIMO LTE systems. The principle of this scheme is simple but can be used only for a fixed range of CQI values. The CQI generation process is illustrated in **Fig. 1**.

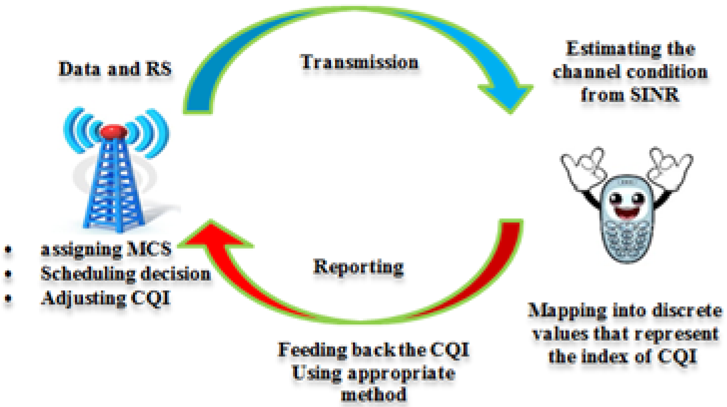


**Fig. 1.** The communication between eNodeB and user based on CQI

Many researchers have introduced intensive proposals to enhance multi-user MIMO in LTE/LTE-A systems based on CQI. Mundarath et al. in [13] have proposed a blind CQI estimation scheme on the user side to enhance the performance of multi-user MIMO transmission in 3GPP LTE systems. Zhiyong in [14] has proposed a CQI estimation method to support multi-user MIMO orthogonal frequency division multiplexing (OFDM) in 3GPP LTE downlink systems. This method relies on the minimum mean square error (MMSE) receiver detector to reduce CQI mismatches between the actual and estimated values. Also, this CQI estimation method is useful in terms of its ability to mitigate mismatches in its capability to achieve correct modulation and coding scheme. Zhu in [15] has proposed a joint optimization method to improve multi-user MIMO transmission with the coordination of a multi-point (CoMP) system in LTE-A. This method consists of a hybrid cooperating set selection scheme; CQI estimation based on instantaneous precoder, and CQI update based on the statistical distribution between real and estimated values. This method is held under a practical assumption and eliminates the negative impact of inter cell interference (ICI) and quantization error, which may occur during feedback. Nguyen et al. in [16] have proposed multi-user MIMO CQI estimation scheme for LTE systems to achieve better decisions in multi-user scheduling. The effectiveness of this method initiated from some factors such as scheduling fairness among users, different antenna configurations, and different correlations. However, this method does not consider the possibility of achieving a dynamic switching between single-user MIMO and multi-user MIMO. Wang et al. in [17] have proposed a CQI estimation method to support the scheduler in creating dynamic scheduling decisions between single-user MIMO and multi-user MIMO in LTE systems. This method provides improved performance to LTE transmission systems by providing a special degree of freedom during the scheduling procedure, in addition to its ability to work in a limited feedback environment.

This paper has carried out a detailed survey on the multi-user MIMO systems in LTE and LTE-A with some advantages and challenges. The effect of CQI on multi-user MIMO LTE system is discussed. Moreover, the consequence of limited feedback bits in describing the real channel information is depicted. A brief comparison between single-user and multi-user MIMO are also highlighted. An Advanced features such as link adaptation and scheduling procedure are addressed briefly due to their impact on improving the system reliability and performance. Both techniques are crucially dependent on the reported CQI. The used CQI generation process and the mapping algorithms are also highlighted. Moreover, the factors that negatively affect the reliability of CQI calculation and estimation alongside with the research opportunities that developed in this area are also discussed. Finally, a comprehensive comparison between the state-of-the-art CQI estimation schemes among discussed multi-user MIMO schemes in LTE and LTE-A systems is performed. Each of these schemes plays an important role in enhancing a specific part of the system. However, none of these schemes can achieve the required performance individually. The ultimate goal of improving the system performance can only be achieved by jointly optimizing the system performances. Furthermore, those proposed studies demonstrate that the achievement of any method depends on some factors that should be adopted to achieve substantial improvements in system gain. An intensive research has been conducted to achieve closely related targets from different angles that consider the enhancement of a multi-user MIMO system based on CQI.

The organization of this paper is as follows. Section 2 briefs the overview of multi-user MIMO in LTE/LTE-A system. Link adaptation and scheduling process are short-term explained in Section 3. The CQI procedure, factors that affect CQI reliability, and conventional and state-of-the-art mapping methods are depicted in Section 4. Section 5 discusses different proposed schemes to enhance the performance of multi-user MIMO in LTE/LTE-A systems. In Section 6, the system performance of the proposed schemes are compared and discussed. Finally, Section 7 concludes the paper and presents recommendations for future works.

## 2. Overview of Multi-user MIMO In LTE/LTE-A System

LTE employs OFDM, which divides bandwidths into subcarriers and modulated in QPSK, 16QAM, or 64QAM based on channel quality [18]. It heavily relies on the MIMO technique, which is essential in providing significant improvements to data rate, coverage and spectral efficiency. The effectiveness of the MIMO technique comes from its ability to combine more data streams arising from multi-path and rejecting the interference. 3GPP with the first release of LTE (Rel-8) specified single-user MIMO as a point to point transmission technique with a target of 300 and 75 Mbps in the downlink and uplink, respectively [19]. Single-user MIMO operates in two different modes, namely transmission diversity and spatial multiplexing modes. In transmission diversity mode, the same signal is transmitted over multiple antennas to improve link quality and guarantee reliability. In spatial multiplexing mode, two different layers are sent from different antennas in the same frequency channel [20]. Considering the capacity limitations of single-user MIMO and the need to support the network infrastructure efficiently, an LTE system is used to define multi-user MIMO as a special transmission scheme to maximize spatial multiplexing gains [21].

Some limitations exist in eliminating the interference caused by co-schedules users. These limitations are caused by the lack of flexibility provided to the eNodeB in selecting multi-user. This problem has recently been solved because LTE-A has assigned two different types of reference signals called demodulation reference signal and channel state information reference signal to further enhance multi-user MIMO performance [22]. Although the multi-user MIMO transmission system has numerous advantages, several challenging issues should be considered in order to improve the system performance. Multi-user MIMO relies on the reliability of channel state information in the eNodeB to mitigate interference. Obtaining a trade-off between the required feedback to guarantee the accuracy and consumed resource via uplink is crucial [23], [24]. The finite feedback bits may not describe the real channel condition, which threatens the gain promised in multi-user MIMO systems [7]. In relation to the aforementioned channel state information, the accuracy of CQI estimation plays an important role in transmission reliability. In terms of cell-edge user spectral efficiency, the exclusive use of multi-user MIMO should be avoided because of the residual interference, which is caused by the deployment of multi-user beam-forming and beam-decreasing power allocated to users [20]. A dynamic switch between single-user MIMO and multi-user MIMO is preferable to balance the average cell user spectral efficiency and cell-edge user spectral efficiency. A summary of some parameter differences between single-user MIMO and multi-user MIMO is listed in **Table 1**.

## 3. Link Adaptation and Scheduling Process in LTE/LTE-A System

In LTE and LTE advanced systems, the same mechanisms of CQI estimation and link adaptation can be used for both single user and multi user MIMO transmission. For instance, authors in [25] used the outer loop link adaptation in single-user MIMO as a guide to match estimated modulation and coding scheme and accommodate errors from the CQI estimation. For the multi-user MIMO system, this method may cause a mismatch because of the time switch between these two systems. This approach may consequently result in the wrong assignment of suitable modulation and coding schemes, thus degrading system performance. The authors in [12] proposed an adaptive fixed offset value. This method can be used for the fixed amount of CQI but is not fully optimized for whole CQI values estimated by single-user MIMO. Therefore, obtaining an accurate CQI in multi-user MIMO is still a challenge. In multi-user MIMO systems, the scheduling decision depends on the channel state, which represents the amount of feedback going to eNodeB from the served users. The users can be classified into two categories, namely primary and candidate users. The primary users are users who need to retransmit their data more than once in accordance with a hybrid automatic repeat request (HARQ) because of their weak channels. Candidate users are users who transmit first [16], [22]. Multi-user MIMO scheduling techniques can be used when all scheduled users are candidates. Switching to single-user MIMO scheduling is necessary when the primary users exist to eliminate interference, which may occur because of multi-user MIMO deployment. Therefore, low-complexity dynamic switching is required between single-user MIMO and multi-user MIMO scheduling techniques to improve the spectral efficiency of the entire network.

**Table 1.** Comparison between single-user MIMO and multi-user MIMO systems.

| **Key Parameter** | Single-user **MIMO** | Multi-user **MIMO** |
|---|---|---|
| Communication Type | Point to point | Point to multipoint |
| Coverage | Less | Higher |
| Average cell throughput | Less | Higher |
| Average cell edge throughput | Higher | Less |
| Propagation channel | Less immunes against the ill-behavior of propagation channel | More immunes against the ill-behavior of propagating channel |
| Antenna correlation (Small spacing-ULA) | Work better in low Correlation | Work better in high Correlation |
| Mobility | Preferable | Not preferable |
| Channel quality | Less sensitive | More sensitive |
| Heavily loaded Cell | Not preferable | Preferable |
| Complexity | Less | Higher |
| Bandwidth | Used more BW | Better usage of the BW available |

### 3.1 Link Adaptation

Link adaptation is an essential process that adapts radio resources to the channel condition in each transmission time interval. This adaptation represents the modulation and coding rate, adaptation to the preceding matrix used, and the number of streams spatially multiplexed. Three types of modulation schemes exist in 3GPP LTE/LTE-A, namely, QPSK, 16QAM, and 64QAM. These schemes are interchangeable depending on the channel condition. For instance, QPSK is considered appropriate and adequate in cases with bad signal strength. In contrast, high-order modulation will be used when SINR is adequately high. In terms of code rate, adaptation is in accordance with the channel condition. If SINR is degraded, the recommended choice is a lower code rate and vice versa. The authors in [26] proposed a low-complex sequential solution for deriving optimization problem to obtain CQI for link adaptation. The proposed method considered a more conservative CQI. Authors in [27] proposed a block-level resource allocation method in LTE to maximize the overall throughput via an adaptation of resource blocks and transmitted power to the user. CQI is an index that has values from 1 to 15 as

$$CQI_r \in \{1, \ldots, CQI_{\max}\}^{R\times 1} \tag{1}$$

where CQImax is referred to the maximum CQI value which is standardized to be 15 and R is defined as a resource block. Each value represents a combination of modulation order and coding rates.

### 3.2 Scheduling Process

Scheduling is an effective way to allocate available radio resources to different users during the transmission process. Scheduling should assign a fair amount of resources among user with respect to their QoS requirements [28]. The scheduling procedure has two types, namely channel-aware and channel-unaware scheduling processes. Channel-aware scheduling considers both the realistic assumption and channel condition represented by CQI, whereas channel-unaware scheduling is held under an ideal assumption without prior knowledge of channel condition. Authors in [29] classified the unaware scheduling type into first-in first-out (FIFO), round robin, blind equal throughput, resource preemption, weighted fair queuing, and guaranteed delay. Aware scheduling is specified into maximum throughput, proportional fair scheduler, throughput to average, joint time and frequency-domain schedulers, delay sensitivity, and buffer-aware schedulers. LTE adopts both strategies to improve system performance [30]. In the channel-aware scheduling, assignment decision is highly dependent on the channel state condition. For instance, if the channel is in good condition, user retransmission is not expected and more resources can be scheduled to improve the spectral efficiency.

The fundamental feature of scheduling schemes is how to adapt radio resource management (RRM) in both time and frequency domains in order to achieve good trade-off between fairness and spectral efficiency based on channel quality [28]. The RRM unit of time and frequency domains in LTE is called a resource block. A resource block represents the smallest radio resource scheduled to any user in accordance with the allocated bandwidth scaled from 1.4 MHz to 20 MHz [18]. Radio resources in LTE are represented in frames of 10 ms in the time domain and are divided into 1 ms sub-frames, wherein each frame is further subdivided into two time slots of 0.5 ms. The 0.5 ms time slot represents 7 or 6 OFDM symbols depending on the cyclic prefix (CP). The CP is a guard time duration that facilitates the nearly complete elimination of a multipath-induced inter-symbol interference (ISI). In the frequency domain, the available bandwidth is divided into physical recourse blocks (PRBs). Each PRB embeds 12 subcarriers with a spacing of 15 KHz which occupy a 180 KHz. The Resource element represents the smallest radio resource scheduled to any user in accordance with the allocated bandwidth [18]. **Fig. 2** depicts the radio resource scheduling unit in the LTE system [28]. The subcarriers are allocated in an aggregation basis for each PRB.

To guarantee the fairness, the authors in [31] proposed a multi-user scheduling method based on CQI probability mass function. Authors in [32] proposed proportional fairness packet scheduling algorithm (PFPS) accounted for user priority and delay according to CQI feedback. Moreover, detailed emphasis for practical feedback is investigated containing CQI measurements and estimation errors, feedback delays, CQI quantization and CQI compression. The authors in [33] proposed an upper and lower level scheduling algorithm based on CQI for real time multimedia service in LTE system. Authors in [34] proposed a user mobility classification method based on CQI for exploiting a multi-user and frequency diversity. This scheduling algorithm is accounting for both low and high user speeds. According to the aforementioned details, link adaptation and scheduling resources are essential features for LTE/LTE-A systems. Both techniques are crucially dependent on the reported CQI. Thus, from multi-user MIMO viewpoints, failing to estimate and report CQI properly will lead to wrong scheduling decisions and incorrect link adaptations. In LTE, the CQI performs an important function in providing channel information to eNodeB. The CQI generation process starts at the eNodeB, which in turn sends a specific reference signal to the user. The user receives this signal and estimates the channel condition. Thereafter, the estimated channel parameters, such as, exponential effective SNR (EESM), and mutual information effective SNR (MIESM), will be mapped into discrete values that represent the CQI index. **Fig. 3** depicts the BLER target and SNR-CQI mapping algorithm [35].

## 4. Channel Quality Indicator (CQI) Procedure

A CQI reflects the variations in the channel condition, which affects the propagated signal during the transmission process between eNodeB and user. The user will send these CQI values to the eNodeB by using a proper feedback mechanism. Then, the eNodeB will apply a scheduling decision and suitable modulation and coding scheme to the incoming information. In the abovementioned transmission process, several factors should be considered in the computation of CQI concerning the propagation effects, such as Doppler shift, time delay, feedback delay, channel estimation error, interference, and quantization error [30].

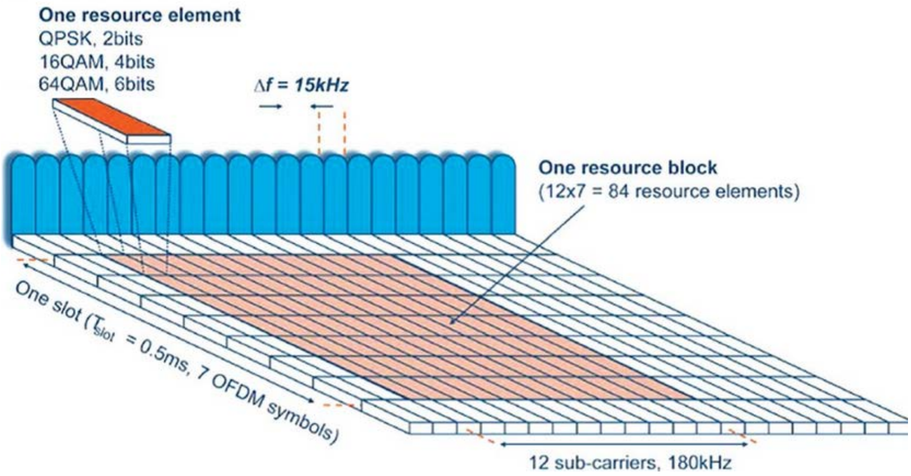


**Fig. 2.** LTE physical resource block [28]

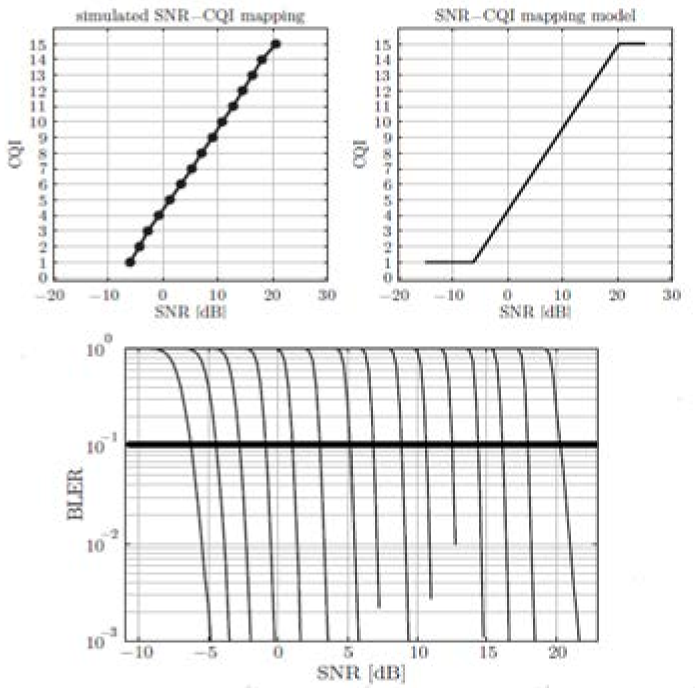


**Fig. 3.** SNR-CQI and BLER-SNR mapping [35]

Recent studies have found that throughput degrades during user mobility because of inaccurate CQI estimation and reporting [36]. Exploiting the channel adaptive signaling in LTE systems yields significant improvements in system performance. In terms of their practical implementation, many types of channel adaptive schemes are deemed unrealistic because of the challenge in obtaining channel information from the eNodeB. Authors in [37] considered that the error in mapping the CQI occurs because of interference and mobility. Consequently, HARQ is proposed with one cyclic retransmission to recover those errors. This method is efficient in controlling the error caused by interference and mobility, but fails to reclaim the error caused by CQI estimation. Authors in [30] illustrated the relationship between delay spread and channel quality. The worst case (i.e., lowest CQI) occurs because of the increase in the variation channels, thus leading to the increase in multi-path delay spread. The authors proposed an effective SNR-delay CQI mapping by defining a cut-off-point via link-level simulation. This method is reinforced by applying a BLER-based CQI convergent algorithm to mitigate the determination offer at the time and granularity, which may cause distortions in CQI accuracy. In [38], authors account for the delay in CQI measuring, processing, and feedback. The author in [39] evaluated the impact of delay in the CQI feedback stage for different user speed to support scheduling processes in OFDMA systems. The evaluation is accomplished by using an improved algorithm of multicarrier PF scheduling and taking the probability distribution function of the estimated CQI. The suggested improvement provides a significant gain in terms of eliminating the effect of outdated CQI, which occurs because of feedback delay.

CQI estimation error is another factor that has a negative impact on channel reliability. Capacity and coverage have been depicted to be highly sensitive to CQI estimation errors [40]. Thus, an intensive research that accounts for this error based on realistic assumption is conducted. The authors in [41] evaluated the impact of CQI estimation, which affects

OFDMA systems. To mitigate this bottleneck and achieve useful signals, the author introduces a compensation mechanism that is represented by the ratio between instantaneous variations in CQI estimation error and noise plus interference. Compensation occurs because of signal regeneration, which shows a significant gain to overcome the CQI estimation problem. CQI estimation error leads to interference, which occurs because of multi-user MIMO implementation. Failing to estimate a reliable CQI will cause a mismatch between SINR feedback and the actual feedback used in the aftermath [42]. Eliminating the mismatch by using only HARQ is difficult [37]. Author in [43] evaluated system performance by using unitary precoders to alleviate the mismatch problem of CQI estimation in multi-user MIMO systems. The use of unitary precoders has a significant effect on the mitigation of interference variation levels for co-scheduled users. Thus, accurate CQI can be observed with reasonable stability. This method is feasible only if the number of antennas at the transmitter and receiver are equal.

In terms of reliable CQI measurements and reports, the quantization error threatens CQI accuracy and leads to the degradation of system performance. CQI quantization is mostly related to the reduction of feedback overhead. Authors in [44] considered the effects of different CQI quantization bits on the rate control of the per antenna rate control of the multi-stream MIMO system. Authors in [45] investigated the performance of MIMO systems under limited feedback with random quantization. The results demonstrated that to maintain the SNR and interference loss, MIMO systems should increase the quantized bits to a certain amount. An efficient CQI quantization method for multi-user MIMO systems has recently been proposed in [46]; this method considers the error caused by quantization for limiting feedback. The effectiveness of this method is related to the quantization size.

Different metrics are used to obtain instantaneous CQI from the mapping of estimated channel parameters, such as SNR, Signal to leakage plus Noise Ratio (SLNR), SINR, EESM, and MIESM [41], [47]. Thus, literature has presented intensive studies on precise techniques that yield the most reliable CQI considering the real environment of the channel. The conventional method of linear mapping is between SNR and CQI. This mapping is conducted by the link-level AWGN channel mode. This mapping should be mapped between BLER and SNR to achieve the condition of the 10% BLER. The results demonstrate that even with retransmission, (e.g., three H-ARQ), the throughput is still smaller than the case of a null retransmission because of the rapid adaptation in modulation and coding schemes based on CQIs. An estimated throughput for the selected modulation and coding scheme can be obtained as

$$Throughput = BW.e(SINR).(1 - BLER(SINR)) \tag{2}$$

where $BW$ is the bandwidth used for allocating resources to the users, and $e.(SINR)$ is the effective code rate used for the selected modulation order. $BLER(SINR)$ is the block error rate where

$$BLER(\{SINR_r\}) \approx BLER(SINR_{eff}) \tag{3}$$

SINR is almost determined in OFDMA for each subcarrier. All SINRs are combined to find the average SINR. An effective SNR is used to map the instantaneous channel quality into a scalar value of $SINR_{eff}$. The $SINR_{eff}$ is given by

$$SNR_{eff} = \beta\ f^{-1}\left(\frac{1}{R}\sum_{r=1}^{R} f\left(\frac{SINR_r}{\beta}\right)\right) \tag{4}$$

where $R$ represents the number of scheduled resource blocks used, whereas factor $\beta$ is adjusted by using link-level simulation to fit the compression function in AWGN and match the SINR to obtain specified modulation and coding scheme according to the CQI value. An efficient link to system mapping in the LTE system for considering SNR has been proposed in [47]. The method is based on the SINR-CQI mapping concept, which offers an enhanced paradigm of EESM and MIESM. These methods correspond to accurate CQI and mitigate the interference between users. Recently, an efficient model expression for EESM as lognormal random variable in LTE system was proposed by authors in [48]. Two CQI feedback methods that used EESM to generate the CQI are analyzed. The results provide insights in achieving a throughput that is close to optimal. The mapping function of the EESM scheme is less complex than MIESM. For BLER to EESM and MIESM mapping, the results illustrate that these methods are conservative for CQI. From the mean of EESM the $SINR_{eff}$ for the CQI feedback is measured as [49]

$$SINR\left(W_m\right)= f^{-1}\left[\frac{1}{R\left|L\right|}\sum_{r=1}^{R}\sum_{l\in L} f_m\left(SINR_{r,l}\left(W\right)\right)\right] \tag{5}$$

where $L$ is the set of layers that transmitted. $f_m$ is belonged to the mapping function. $W$ refers to the precoder defined by codebook based precoding. In order to ensure that the BLER is satisfied, the function $T_m$ has been introduced. This function tests the BLER and passes the spectral efficiency for effective modulation and coding scheme. Thus, the estimated spectral efficiency of LTE is given as

$$E\left(W,m\right)=T_m\left(B\left(W,m\right)\right).\left(1-B\left(W,m\right)\right) \tag{6}$$

The summation in this case contains all resource blocks. Therefore, the optimal formula will be as

$$\left[L,W,m\right]=\arg\max_{L,W_s,m}\sum_{c=1}^{L} E\left(\left\{W\right\},m[c]\right) \tag{7}$$

Here, there is dependence on all resource blocks for whole CQI values. The obtained values correspond to the set of CQI values arranged in a vector $m$ with a length equivalent to the $L$ transmission layers.

## 5. Multi-user MIMO Transmission System with Different CQI Estimation Schemes

Multi-user MIMO is a transmission technique proposed by the 3GPP LTE/ LTE-A system and aims to achieve spectral efficiency requirements [30]. The multi-user MIMO transmission technique can transmit different streams in the time and frequency domains. From a practical perspective, the bottleneck that prevents the multi-user MIMO system for accomplishing its aim is the achievement of an accurate CQI estimation to manage the allocated resources to users by link adaptation and scheduling decision. Various strategies have been monitored by intensive research to enhance multi-user MIMO performance by appropriate schemes to obtain an efficient CQI estimation and avoid mismatches, which may occur during the transmission process. However, the success of any scheme depends on some factors and criteria such as realistic assumption, receiving type, feedback mechanism, interference reduction, adjustment technique, overhead and complexity [13]-[17]. This section will address a comprehensive review of some schemes proposed in literature to enhance the performance of multi-user MIMO systems with appropriate CQI estimation in the LTE/LTE-A system.

### 5.1 Blind CQI Estimation Method for Multi-user MIMO Transmission System

Mundarath et al. in [14] have proposed a blind CQI estimation scheme on the user side to improve the performance of multi-user MIMO transmission in 3GPP LTE systems. The blind CQI estimation scheme estimates CQI from SINR by applying scheduling decisions and AMC level selection. Moreover, the authors are motivated to enhance other factors that are considered obstructions of multi-user MIMO in achieving system performance. This scheme considers the knowledge of transmit beam-forming matrix at the eNodeB side by applying a good adjustment technique for CQI feedback by a user. By using this technique, the system will be able to improve the accuracy of CQI estimation and accommodate variations in CQI feedback from different users. The blind CQI estimation scheme is evaluated under different classes. For instance, a brief explanation on how CQI adjustments affect the spectral efficiency is provided. The lack of accuracy in CQI adjustment will lead to losses in packet transmission, thus increasing the number of retransmission processes will cause an over allocation of resources. The fair comparison between Mundarath's scheme and a conventional scheme based on zero-forcing beam-forming with a benchmark of perfect feedback knowledge has been described in **Fig. 4**. This figure illustrates performance metrics based on the average sum rate with SNR. Mundarath's scheme outperforms the zero-forcing beam-forming scheme for all SNR values as proposed in [50]. The difference in performance occurs because the multi-user MIMO transmission system based blind CQI scheme employs the joint optimization of the receiver beam former and codebook selection algorithm to achieve a trade-off between SNR maximization and quantization error minimization. The scheme proposed in [50] consumes more resources to minimize the quantization error without considering any SINR gain. In contrast, a difference exists in the performance between Mundarath's scheme and the ideal scheme full feedback.

This difference increased after SNR reaches 15 dB because of the limitation in the number of feedback bits, which limit system operations. Further performance degradation occurs in Mundarath's scheme compared with the ideal scheme because of quantization error. Thus, Mundarath's scheme is unrealistic in practice. The residual interference between user channels is caused by the unaware scheduling procedures of multi-user. This residual interference still exists even when the receiver implementation technique of zero-forcing beam-forming is applied.

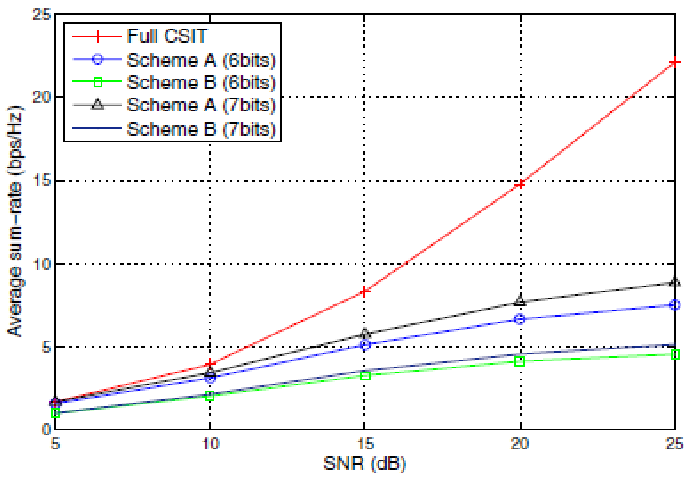


**Fig. 4.** Comparison of for a 6 x 2 system with full channel state information [13]

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### 5.2 CQI Estimation Method Based on Limited Feedback for Multi-user MIMO Systems

Zhiyong in [14] has proposed a CQI estimation method based on limited feedback to support multi-user MIMO OFDM in 3GPP LTE systems. This method uses the MMSE receiver detector to reduce the CQI mismatch between the estimated CQI in the user side and the real CQI used in the downlink at eNodeB. This method improves CQI accuracy to enhance the scheduling procedure and increase the robustness of link adaptation decisions by selecting appropriate modulation and coding scheme. In contrast to other conventional methods, where all data are assigned to the same user at the same chunk, this method holds practical assumptions with multi-user MIMO. Moreover, the author develops a feasible multi-user MIMO zero-forcing precoding scheme to cover CQI calculation, channel direction information quantization, user selection, and link adaptation.

The authors investigated the CQI mismatch between the CQI estimation method based on limited feedback and the CQI based on an approximation method at the eNodeB by taking the probability distribution function. The author demonstrates the variance between these schemes and how the mismatch in the CQI estimation method based on limited feedback has less divergence than the conventional one based on approximation method according to the probability density assumption. Another observation can be drawn from Chen's scheme by comparing the performance of the suggested method, which is the zero-forcing multi-user MIMO CQI estimation with SINR approximation method in [7]-[9], and the response to the basic method of SU-MIMO as shown in **Fig. 5**.

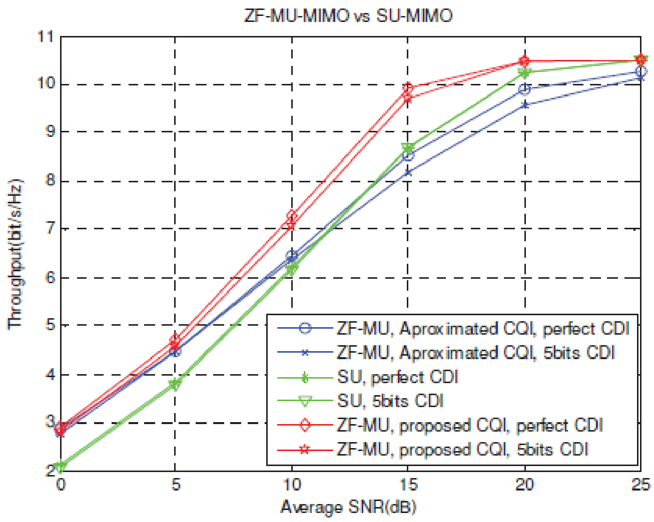


**Fig. 5.** The throughput vs. SNR plots for different cases in multi-user MIMO OFDM system [14]

Chen's scheme performs better by approximately 1 bit/s/Hz in the throughput than the base method of single-user MIMO for all SNR values. The proposed scheme achieves significant performance improvements. This improvement is caused by a variety of factors such as the adequate CQI estimation method with multi-user MIMO transmission system, efficient type of detection technique at the receiver, and appropriate adjustment of CQI feedback from user to eNodeB.

### 5.3 CQI Estimation Method Based on the Statistical Distribution in CoMP for Multi-user MIMO Transmission Systems

Zhu in [15] has proposed a joint optimization of hybrid cooperating set-selection schemes, that is, CQI estimation based on instantaneous precoder and CQI updates based on the statistical distribution between estimated CQI and real CQI. This method improves multi-user MIMO transmission by using the Cooperative Multi-Point (CoMP) system for LTE-A. The joint optimization method eliminates the effect of inter cell interference ICI and quantization error with limited feedback. This scheme achieves both average and cell-edge throughput because of considerable improvements in CQI accuracy for modulation and coding scheme selection. Furthermore, this scheme obtains balance in performance, feedback overhead, and complexity. The application of updated CQI values from offline simulation is performed to generate a lookup table that can describe the relationship between such CQI values. The reliability of the joint optimization method depends on the accuracy of estimated CQI value, which can be employed afterwards in a flexible multi-user scheduling. The author considers some factors that affect the reliability in obtaining CQI, such as ICI, noise, and quantization error. The negative impact of quantization error, which affects CQI feedback accuracy from a user, has been depicted. The results show that Zhu's scheme stands against ICI in terms of limited feedback. The estimated CQI for the joint optimization method is applicable to the real CQI. Thus, a significant gain in the throughput for CoMP multi-user MIMO LTE-A systems can be achieved.

### 5.4 CQI Estimation Based on Adaptive Method of Multi-user MIMO

Nguyen et al. [16] have introduced another CQI estimation approach that is used to reinforce multi-user MIMO systems. This approach aims to provide an accurate CQI estimation for multi-user MIMO in LTE, thus leading to accurate multi-user scheduling and link adaptation. The authors proposed an adaptive mechanism for obtaining multi-user CQI based on the reported channel condition of single-user MIMO. The relationship between single-user MIMO CQI based on rank 1 and multi-user MIMO CQI estimation is analytically analyzed. The closed-form expression estimation is derived for multi-user MIMO. The conventional method is used for the fixed offset values to estimate CQI for multi-user MIMO from rank 1 CQI single-user MIMO. This method depends on two factors; accounts for the shared power among user, and considers the estimation of MUI [5]. The results show that the conventional fixed offset is not optimal for all rank 1 single-user MIMO values. This negative behavior occurs because of the overestimation of the real values of single-user MIMO. The comparison between the adaptive method and fixed method is shown in Fig. 6. Average cell throughput for the adaptive scheme outperforms the conventional method for different antenna correlated cases. The adaptive scheme achieves a trade-off between multi-user CQI estimation and overall system throughput. Moreover, the adaptive scheme enhances codebook-based precoding and non-codebook-based zero-forcing precoding.

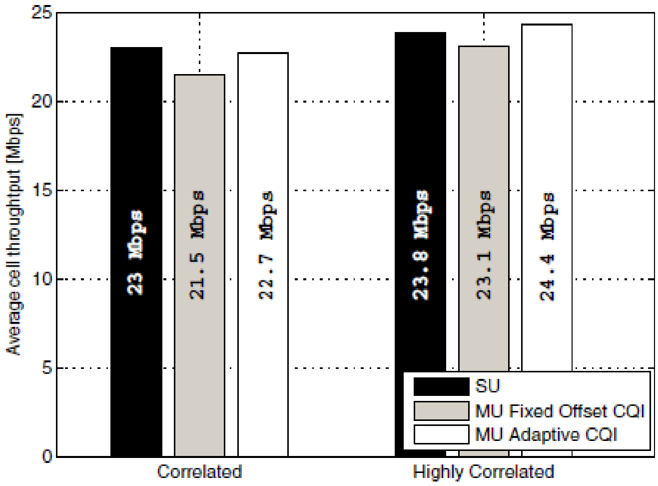


**Fig. 6.** Average cell throughput for single-user MIMO and multi-user MIMO [16]

### 5.5 CQI Estimation Method Based on Dynamic Multi-user MIMO Scheduling

The latest CQI estimation method has been proposed by Wang et al. in [17]. This method converges with previous methods to achieve a robust multi-user MIMO transmission system. This method supports a dynamic scheduling decision between Rank 1 single-user MIMO and multi-rank multi-user MIMO in LTE systems. This scheme is more flexible than other schemes because it provides a special degree of freedom during the scheduling procedure, in addition to the limited feedback. The Conventional methods are based on the fixed assumption of number of receiving antennas and ranks. A significant increase in the effort of determining the estimated CQI for all users has been found. Therefore, an adaptation to manage the feedback load and complexity with respect to performance is conducted for different numbers of users, antennas, and ranks. The implementation of Wang's scheme is divided into two tasks, namely codebook clustering and CQI estimation.

This division is caused by the reduction in complexity because each user has to estimate SINR and feed it back to the serving eNodeB as measured CQI values. The eNodeB will ultimately assign the scheduling and precoding, which rely on CQI values. The author’s approach is dependent on the sum rate metric based on a variety of CQI values with different SNRs to compare the dynamic multi-user MIMO scheduling based CQI and conventional schemes (best-companion user pairing scheme) [50]. **Fig. 7** shows that the sum rate increases with increasing SNR based on 100 users. The dynamic scheme outperforms the conventional scheme. The increased performance occurs because the conventional scheme is restricted to the scheduling decision. Thus, lack of freedom and flexibility in selecting different transmission streams will exist. In brief, the dynamic multi-user MIMO scheduling based CQI estimation scheme is suitable for the state-of-the-art requirement of the 4G system LTE-A because this scheme supports the dynamic switching between single-user MIMO and multi-user MIMO, and thus have increased antenna configurations.

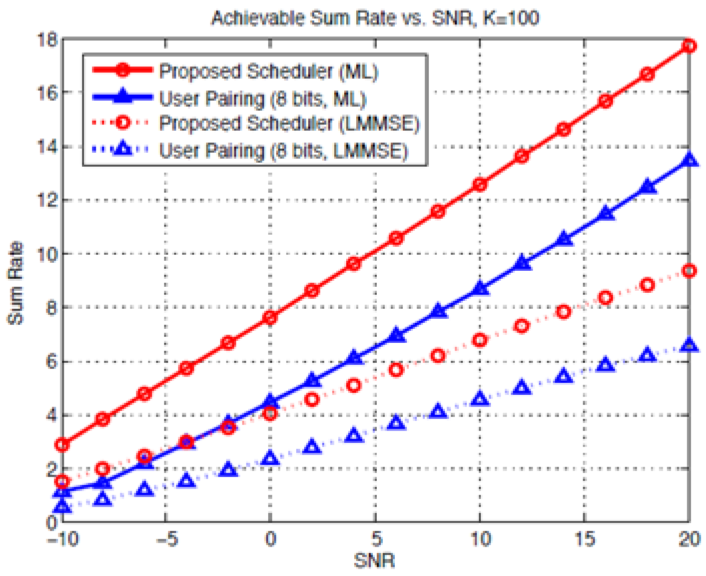


**Fig. 7.** Sum rate vs. SNR, M = 4, number of users is fixed at 100 [17]

## 6. Comparison of CQI Estimation Methods

All proposed schemes aim to enhance system efficiency and overall performance by tackling issues pertinent to multi-user MIMO in LTE and LTE-A systems. Mundarath in [13] has studied the enhancement of multi-user MIMO in 3GPP LTE systems by using a blind CQI estimation scheme to assist the eNodeB in scheduling decisions and AMC level selection. This blind CQI estimation method is efficient in CQI adjustment by providing a reliable estimated CQI and feeding the CQI back to the eNodeB after estimation. It can be done by jointly designing the receive beamformer and channel codeword to optimize the CQI. The performance of multi-user MIMO system will be improved by finding the optimal receive beamformer for the limited feedback case with an accurate CQI estimation. Thus, it achieves significant gain in multi-user MIMO under practical assumption and limited feedback for optimizing system performance. However, the limited feedback case causes multi-user interference to exist even when the zero-forcing beam-forming technique is implemented in the transceiver design.

Zhiyong in [14] has proposed an alternative CQI estimation method to improve system performance of multi-user MIMO OFDM in 3GPP LTE downlink systems. It focuses on eliminating the interference caused by multi-user, and the mismatch between estimated and actual CQIs to achieve correct modulation and coding scheme. Despite the robustness of the joint optimization technique are realized with different number of users in the cell, this method does not consider the fairness in scheduling. Thus, this technique is feasible only under a fixed number of antennas in both transmitters and receivers. Unlike previously CQI estimation methods, Zhu in [15] has assumed different antenna configurations to provide significant gain to cell-edge user. The author has proposed a joint optimization method to improve multi-user MIMO transmission with CoMP system in LTE-A by furnishing such a system with the ability to prevent ICI and eliminate quantization error. This method is held under a practical assumption and eliminates the negative impact of ICI and quantization error, which may occur during feedback. Moreover, the author has addressed the joint optimization of hybrid cooperating set selection scheme; CQI estimation based on instantaneous precoder, and CQI update based on the statistical distribution between real and estimated values. However, the switching relationship between the multi-user MIMO CQI and single-user MIMO CQI given by the lookup table is determined by offline simulations to obtain the estimated CQI of multi-user from single-user.

Therefore, further information about the correlation between multi-user MIMO CQI and single-user MIMO CQI values are lacking. Unlike Zhu, Nguyen in [16] has studied the relationship between multi-user MIMO CQI and single-user MIMO CQI values with various channel conditions, and proposed an accurate multi-user MIMO CQI estimation scheme to improve the overall performance of the LTE system. The effectiveness of this CQI estimation method originates from different factors such as scheduling fairness among users, different antenna configurations, and different correlations. However, this method does not consider the possibility of achieving a dynamic switching between single-user MIMO and multi-user MIMO. Wang in [17] recently has proposed a dynamic multi-user MIMO scheduling based on the CQI estimation method to improve the performance of multi-user MIMO transmission systems by supporting dynamic scheduling decisions between single-user MIMO and multi-user MIMO in LTE systems. It provides an improved performance to LTE transmission systems by providing a special degree of freedom during the scheduling procedure, in addition to its ability to work in a limited feedback environment. However, the trade-off is drawn based on the sum rate. Therefore, a further investigation of the bit error rate and CQI-related relationships are necessary in this method. A comprehensive comparison among these five CQI estimation schemes which discussed multi-user MIMO schemes in LTE and LTE-A systems are summarized in **Table 2**. It shows that each of these schemes has a different way in improving specific part of the system. Hence, none of them can achieve the required performance individually. However, the dynamic multi-user MIMO scheduling method proposed by Wang in [17] seems to be the most appropriate CQI estimation scheme to achieve high scheduling adaptation compared to other methods. This is because the adaptation decision used by Wang is based on realistic estimation technique which takes into account the variation in channel signal strength. Therefore, link adaptation based on CQI estimation is highly recommended for multi-user MIMO scheduling scheme.

**Table 2.** Comparison of different CQI estimation methods

| Author(s) | Method | Challenge | Trade-off |
|---|---|---|---|
| Mundarath - 2008 [13] | A blind CQI estimation method by jointly designing the receive beamformer and channel codeword. | Performance optimized by<br>1. Accurate CQI estimation.<br>2. Receive beamformer.<br>3. Channel codeword selection. | Performance vs. interference in the limited feedback case |
| Zhiyong - 2010 [14] | A CQI estimation method to reduce mismatch between estimated and actual CQIs. | Reduce the impact of mismatch between estimated CQI and actual CQI to improve the reliability of Link adaptation. | Estimated CQI vs. actual CQI |
| Zhu - 2010 [15] | A hybrid cooperating set selection scheme; CQI estimation based on instantaneous precoder and CQI update based on statistical distribution. | Multi-user MIMO transmission is improved by furnishing the CoMP system to prevent ICI and eliminate quantization error. | Multi-user MIMO CQI vs. single-user MIMO CQI |
| Nguyen - 2012 [16] | A MU-MIMO CQI estimation scheme. | Effective by different factors such as<br>1. Scheduling fairness among users.<br>2. Different antenna configurations.<br>3. Different correlations. | Multi-user MIMO CQI vs. overall system performance |
| Wang - 2012 [17] | A CQI estimation method based on dynamic scheduling decisions between single-user MIMO and multi-user MIMO. | Performance improved by<br>1. A special degree of freedom during the scheduling procedure.<br>2. Its ability to work in a limited feedback environment. | Bit error rate vs. CQI |

## 5. Conclusion

The 3GPP LTE/LTE-A system introduces a multi-user MIMO transmission scheme as an enabling technique to satisfy spectral efficiency requirements. However, improving the performance of multi-user MIMO is still important. The key obstacles that prevent the gains presumed by multi-user MIMO is inaccurate CQI estimation. This inaccuracy causes inappropriate resource scheduling and link adaptation, which will lead to severe performance degradation. In this paper, multi-user MIMO enhancement is studied intensively. A brief discussion on scheduling, link adaptation process are addressed. The factors that negatively affect CQI reliability are also highlighted. Moreover, various multi-user MIMO CQI estimation schemes have been covered. Each scheme plays an important role toward obtaining persuasive performance. Furthermore, those proposal studies show that the success of any scheme depends on factors and criteria that should be adopted to achieve substantial improvements in system gain. Some performance metrics have been outlined to provide a better understanding of the practical deployment of the current multi-user MIMO LTE/LTE-A system. An intensive research has been conducted to achieve closely related targets from different angles that consider the enhancement of multi-user MIMO system based on CQI. However, further investigation is still required because of the challenges emerging from deployment of current generation mobile LTE-A systems. Moreover, a further improvement on the dynamic switching between single-user MIMO and multi-user MIMO is also important.

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