Abstract—In this paper we evaluate the performance of Channel Quality Indicator (CQI) reporting schemes in 3GPP UTRAN Long Term Evolution (LTE) Downlink (DL). In LTE, time and frequency dependent CQI is needed for DL Packet Scheduling (PS) and fast Link Adaptation (LA). Recent studies have indicated that Frequency Domain PS (FD-PS) and LA are essential techniques in improving the LTE performance, giving e.g. both cell throughput and coverage gain of around 40% over a distributed multiplexing scheme. However, there is a tradeoff with signaling overhead related to the CQI feedback and overall LA and PS performance, which is rather overlooked in the literature. We analyze four different CQI reporting schemes with respect to system spectral efficiency and conclude that the Best-M average and Threshold based CQI reporting schemes seem to be the most promising in terms of the compromise between system performance and signaling overhead.

I. INTRODUCTION

The Evolved UTRAN (E-UTRAN) or the UTRAN Long Term Evolution (LTE) specifications are being finalized in 3GPP. LTE aims at ambitious goals of e.g. peak data rate of 100 Mbps in DL and 50 Mbps in uplink (UL) [1] [2] [3]. The main principles of E-UTRA DL and UL as well as the core network have been decided already. LTE supports both Time (TDD) and Frequency Division Duplex (FDD) modes, but here we concentrate on FDD. Orthogonal Frequency Division Multiple Access (OFDMA) has been selected as the DL access technology and Single Carrier Frequency Division Multiple Access (SC-FDMA) for UL [4]. OFDMA provides scalability, simple equalization and also the means for advanced frequency domain adaptation.

To achieve the objectives set for LTE, advanced Radio Resource Management functions (similar to those from 3G evolution) have been defined. The algorithms include e.g. Hybrid ARQ (HARQ), LA and CQI. HARQ is utilized for fast retransmissions of erroneous packets to keep the radio interface delay in minimum. User Equipment (UE) measures the received channel quality, e.g. SINR, and reports the channel dependent CQI reports in UL to provide the time and frequency variant channel quality information for different DL Radio Resource Management (RRM) functions, such as PS and LA. LA uses CQI to choose the most efficient Modulation and Coding Schemes (MCS) and PS to select the scheduling time and frequency for each UE. [3]

FD-PS and LA are essential techniques that can improve the performance of LTE. According to [5] the frequency domain scheduling can provide both cell throughput and coverage gain of around 40% over a distributed multiplexing scheme. However, the cost of achieving gains of this magnitude is increased signaling overhead, and especially the required CQI feedback in UL. Thus there is a tradeoff between the system performance and UL signaling overhead. The CQI reporting frequency in time and resolution in frequency should be high enough to provide FD adaptation gain, but as low as possible to minimize the UL signaling overhead.

The objective of this article is to study the effect of CQI reporting frequency and resolution on system performance. Several candidate CQI reporting schemes are also studied in order to evaluate how much feedback information can be reduced, while still being able to gain from FD-PS and LA. Previous CQI studies include e.g. [6], [7] and [8].

The rest of the paper is organized as follows. Section II presents the CQI measurement modeling and different reporting schemes. In Section III the simulation environment is presented and Section IV provides the results. Finally, Section V concludes the article and presents future work ideas.

II. CQI MEASUREMENT MODEL

A. General

CQI is generally used in choosing the correct MCS under the current channel conditions and calculating priority metrics for packet scheduling algorithms. In the simulator, CQI measurement model consists of four basic steps: measuring SINR, introducing measurement error to SINR, converting SINR values to discrete CQI steps and finally CQI reporting with a specific scheme. Ideal linear SINR is calculated for each Physical Resource Block (PRB) $n$ from the received pilot power and total interference every measurement period. The
measured linear SINR value for each PRB \( n \) is converted into decibels:

\[
SINR_{dB}(n) = 10 \cdot \log_{10}[SINR_{lin}(n)] + Error_{dB}.
\] (1)

Error_{dB} is a Gaussian distributed error with zero-mean and parameter specified variance, which is introduced to the measured ideal SINR. SINR values are converted to discrete CQI values by quantization steps (QStep_{dB}):

\[
CQI_{dB}(n) = QStep_{dB} \cdot \text{floor}\left(\frac{SINR_{dB}(n)}{QStep_{dB}} + 0.5\right). \tag{2}
\]

In the simulator, CQI is measured at parameter defined time intervals, which have the length of the multiplies of a Transmission Time Interval (TTI). The measured CQI values are reported with a certain delay and by a CQI reporting scheme. The basic scheme reports CQI for an amount of consecutive PRBs and the compressive schemes have more advanced reporting techniques. It is possible to alter the granularity of basic reporting scheme by changing the number of CQI reports per TTI. Full feedback reporting is done by measuring and reporting individual CQI values for all PRBs. The least granularity is achieved by wideband CQI, which is an average value calculated among all PRBs.

### B. Best-M CQI reporting scheme

The performance of Best-M CQI reporting scheme has been studied in [9]. The reporting compression in Best-M scheme is based on identifying those PRBs, which have the highest CQI values. The parameter \( M \) represents the number of PRBs with the highest CQI values to be identified. The \( M \) PRBs are reported individually (Best-M individual) or as an average (Best-M average) depending on the implementation of the scheme. The reporting for the remaining (unclaimed) PRBs with the lowest CQI values is done by calculating the average CQI among the remaining PRBs. The use of the unclaimed PRBs has been studied in [10].

Clearly, the amount of CQI related signaling is lower with Best-M average than Best-M individual. However, it is assumed that Best-M individual scheme with more accurate CQI reporting can give better system performance results in terms of spectral efficiency and cell coverage. The estimated amount of CQI reporting related signaling (CQI word size) in bits for Best-M individual scheme is

\[
5 + \left[ \log_2 \left( \frac{N_{sb}}{M} \right) \right] + 5. \tag{3}
\]

CQI word size represents the amount of signaling bits per measurement period for UE CQI reporting. In Best-M scheme, CQI word size depends on the amount of CQI sub-bands per measurement period \( N_{sb} \) and the parameter \( M \). The estimation is based on the assumption that 5 bits is needed to represent the link adaptation dynamic range (5 bit range corresponds to 32 discrete CQI values). In addition to signaling required by reporting the best-M CQI values and the average CQI of the remaining PRBs, a label indicating the best-M sub-bands is also needed. The same assumptions are also true in calculating the CQI word size in bits for Best-M average scheme with

\[
5 + \left[ \log_2 \left( \frac{N_{sb}}{M} \right) \right] + 5. \tag{4}
\]

### C. Threshold based CQI reporting scheme

In Threshold based scheme [7] [9], the CQI reporting compression is based on two average CQI values like Best-M average, but the approach for identifying the sub-bands for averaging is different. The best-M CQI values for the high average are replaced by identifying the PRBs, which have CQI values included in the threshold relative to the highest measured CQI. The size of the threshold is defined by a parameter in decibels. An average CQI is also reported for the remaining PRBs with the lowest CQI, which is calculated among the PRBs. As the exact amount of the sub-bands representing highest CQI values is adaptive in Threshold based scheme, more rough estimate of the CQI word size is needed. The estimated CQI word size in Threshold based reporting scheme is \( 30 + 5 \) bits (additional 5 bits is needed to report the low average).

### D. Discrete Cosine Transform based CQI reporting scheme

Discrete Cosine Transform (DCT) based CQI reporting scheme has been studied in [11]. The CQI values for resource blocks are DCT transformed, compressed and quantized before sending the values to eNode B (eNB). There are various methods for sending the DCT processed information, but in this article only significant-M is used in the simulations. In DCT significant-M scheme, the compression is done by sending only \( M \) DCT output coefficients, which have the highest absolute value. For the received DCT coefficients, de-quantization and de-compression is done at eNB. Decompression is done by adding zeros for the coefficients, which are not claimed with significant-M. Finally, inverse DCT (IDCT) is performed for the coefficients and the CQI values for PRBs are attained. The estimated CQI word size for DCT significant-M is

\[
5 + M + \left[ \log_2 \left( \frac{N_{sb}}{M} \right) \right]. \tag{5}
\]

### III. Simulation model

The simulator used in this study is a fully dynamic simulator, where also user mobility and handovers are modeled. Simulations are done in OFDM symbol resolution and Exponential Effective SINR Mapping (EESM) is used as link-to-system interface [12]. Users are randomly distributed over the simulation area of 9 macro cell sites. The main simulation parameters are based on the simulation cases defined by 3GPP shown in Table I. The simulations are done in three different cases with varying UE velocity and pathloss.

The CQI reporting scheme evaluation is based on the UTRAN LTE DL parameters and assumptions presented in [1]. A detailed description of the parameters used in the
simulations is shown in Table II. The simulations are done in synchronous network with the total of 27 cells and an average of 15 UEs per cell. Traffic model is infinite buffer, where each user has always enough data to transmit. For channel modeling, Typical Urban (TU) is used. Every UE in the network uses MRC 1x2 receiver to increase the received SINR. Packet scheduling model is divided into Time Domain (TD) and FD presented in Fig. 1. Proportional Fair (PF) packet scheduling algorithm is utilized in both TD and FD with maximum number of 5 scheduled users per TTI. Link adaptation with outer loop implementation selects the MCS for a user based on CQI measurements and controls the BLER target for the first transmission. Asynchronous chase combining HARQ is used with six stop-and-wait processes per user.

The basic CQI reporting scheme is evaluated by varying the number of PRBs per CQI and measurement period in 3GPP Case 1. Full feedback and wideband CQI reporting are evaluated also in different 3GPP cases. Best-M, Threshold and DCT based CQI reporting schemes are evaluated in rather ideal conditions with CQI reporting delay and measurement period of 1 ms. CQI is measured as a mean of two consecutive PRBs, which provides 25 CQI reports per TTI in 10 MHz bandwidth.

### IV. RESULTS

#### A. Basic reporting scheme

The results for varying FD and TD granularity in CQI reporting are presented in Fig. 2. The reference full feedback CQI result used in all simulations is 2 PRBs per CQI with measurement period of 1 ms, which has under 1 % loss in spectral efficiency compared to 1 PRB per CQI granularity. Wideband CQI reporting (50 PRBs per CQI) has 20 % loss in spectral efficiency compared to the reference full feedback of 2 PRB per CQI. The results show that the effect of measurement period decreases when the FD granularity for CQI reporting is reduced (less PRBs per CQI).

Fig. 3 illustrates spectral efficiency results in 3GPP Cases 1, 2 and 120 with full feedback or wideband CQI reporting. The results show that in Case 1, full feedback has 25 % gain in spectral efficiency over wideband, while in Cases 2 and 120 the gain is under 1 %. This is due to the increased UE velocity in Cases 2 and 120, which causes the loss of the frequency selectivity of CQI even with full feedback reporting. Therefore the spectral efficiency gain is not significant with full feedback reporting in the Cases 2 and 120.

#### B. Best-M CQI reporting

Fig. 4 illustrates the spectral efficiency results of Best-M individual and average schemes compared to the basic scheme with full feedback or wideband CQI reporting. The different approach of reporting best-M CQI values in the two schemes can be clearly seen in the results. Increasing the number of individually reported CQI sub-bands to 10 in Best-M individual scheme, decreases the loss in spectral efficiency to 2 %. As expected, the loss is reduced even further when the $M$ parameter is over 10. Best-M average scheme reaches the smallest loss in spectral efficiency (3 %) with reporting
CQI reporting

The smallest loss in spectral efficiency with Threshold based scheme compared to full feedback is achieved with the threshold size of 4 dB (3 %). The results for Threshold based scheme are shown in Fig. 5. Reducing the threshold size from 4 dB causes the amount of unclaimed PRBs to be too high for reaching the best results in spectral efficiency. On the contrary, the threshold sizes higher than 4 dB cause the average CQI reported for the best CQI sub-bands to be too inaccurate.

D. DCT significant-M CQI reporting

Fig. 5 illustrates the spectral efficiency results of DCT significant-M scheme in comparison to full feedback and wideband CQI reporting. The results show that spectral efficiency raises rapidly when the amount of DCT output coefficients to be sent is increased from 1 to 5. The loss in spectral efficiency with DCT significant-M 1 (just the DC component sent) is over 20 % compared to full feedback CQI reporting. The loss decreases to about 5 % or 3 % as the amount of coefficients sent is increased to 5 or 10, respectively.
E. Comparison of CQI schemes

In Fig. 7, the CQI reporting schemes are presented in terms of spectral efficiency loss compared to full feedback. The CQI word size in different CQI reporting schemes is estimated and the results in relation to spectral efficiency are presented in Fig. 8. The results show that DCT significant-M 9 or Best-M individual 8 are needed to provide better spectral efficiency results than Threshold based scheme with the threshold size of 4 dB or Best-M average 10 in stable conditions. The estimated CQI word size is 35 bits with Threshold based and Best-M average 10 reporting schemes, which is about 45 % less than the CQI word size of DCT significant-M 9 or Best-M individual 8.

![Figure 7: Relative loss in spectral efficiency compared to full feedback CQI.](image)

![Figure 8: Spectral efficiency vs. CQI word size with different reporting schemes.](image)

The studied CQI reporting schemes were Best-M individual, Best-M average, Threshold based and DCT based.

The results show that
- CQI measurement interval of 2 ms and frequency resolution of 2 PRBs per CQI is sufficient to capture both the frequency selectivity and time variant behavior of the DL channel
- With higher UE velocity the frequency selectivity of CQI is already lost, but it still provides gain, because UEs can still be ordered according to path loss in PS
- Best-M average and Threshold based CQI mechanisms provide good system performance with really low UL signaling overhead

Examples of future work include the effect of more variable conditions on CQI scheme parametrization and system performance, such as bursty traffic models, different number of UEs per cell, maximum schedulable users in PS and different channel models.

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**REFERENCES**