# Effects of Non-Ideal Channel Feedback on Dual-Stream MIMO-OFDMA System Performance

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***Abstract*— In this paper we analyze the downlink OFDMA system-level performances of a 2x2 dual-stream MIMO multi-user transmission scheme under the assumptions of partial and noisy channel quality indicator (CQI) feedback available from the terminals. The effects on the CQI feedback of the terminal measurement and estimation errors, quantization errors, uplink reporting format and delays are included. Two reduced CQI reporting schemes are evaluated in Macro and Micro Cell scenarios when operating in combination with a MIMO Outer Loop Link Adaptation (OLLA) and a MIMO aware frequency domain packet scheduling (FDPS) algorithm. We show that, by using OLLA and with a proper choice of the CQI reporting scheme for dual-stream MIMO, the required CQI feedback overhead can be reduced by 90% while limiting the cell throughput losses to less than 10%.**

## I. INTRODUCTION

Advanced OFDMA systems are envisaged currently in standardisation for UTRAN Long Term Evolution (LTE) [1], [2], WiMAX [3] and in several research projects e.g. WINNER [4], SURFACE [5], MASCOT [6]. All these systems assume operating bandwidths of at least 20 MHz with flexible data rate adaptation per sub-band, which is hard to achieve in practical implementations due to practical signaling constraints and the radio channel estimation errors.

Recent studies have disclosed the potential of frequency domain adaptation under less ideal conditions for various SIMO and MIMO transmission schemes, e.g. [7], [8], [9], [10], [11], [12]. The multi-user system level studies performed for a downlink (DL) FDD OFDMA LTE compliant system using a 10 MHz bandwidth have shown potential frequency domain packet scheduling (FDPS) gains in both average system capacity and cell-edge data rates on the order of 35% [13], [14], and depending significantly on the frequency-domain scheduling resolution as well as the accuracy of the channel state reports [8], [15]. A typical channel state indicator, which is used for both downlink (DL) in cellular systems, is the CQI representing a (direct or indirect) measure of the estimated optimal transmission parameters for the allocated resources. The measurement mechanism of the CQI parameter has significant impact on the performance of multi-user transmit-receive schemes and has been analysed in the literature, e.g. [15], [16].

In this paper we use DL FDD UTRAN LTE [1], [2] as case study, and we analyze the multi-user downlink system-level performances of a dual-stream (dual-codeword) 2x2 MIMO transmission scheme[1] under the assumption of partial and noisy CQI feedback available from the terminals. A threshold CQI reporting scheme based on the average Signal to Interference and Noise Ratio (SINR) has been investigated for various MIMO schemes in [11], [12]. Here we extend two CQI reporting schemes previously used for single-stream trasnmission, *Best M* and *Threshold based averaging* and we evaluate them for a dual-stream MIMO multi-user transmission scenario. Further, the single-stream OLLA algorithm for controlling the average transmission Block Error Rate (BLER) presented in e.g. [11], [13] and [14] is extendend here for operation with dual-stream MIMO. For these studies we have adopted the system level CQI model, in terms of measurement errors, quantization errors and reporting delays, as analyzed and proposed in [17] and [18].

The rest of the paper is organized as follows. Section II describes the main blocks in the MIMO radio resource management algorithm. In Section III we analyze two reduced CQI reporting schemes, which are appropriate for FDPS. Then, in Section IV we present the main simulation assumptions used and finally, in Section V we discuss the obtained results. The conclusions are summarized in Section VI.

## II. RADIO RESOURCE MANAGEMENT ASPECTS

Fig. 1 shows the operating principles of the downlink link adaptation (LA) and packet scheduling (PS) mechanism analyzed in this paper.

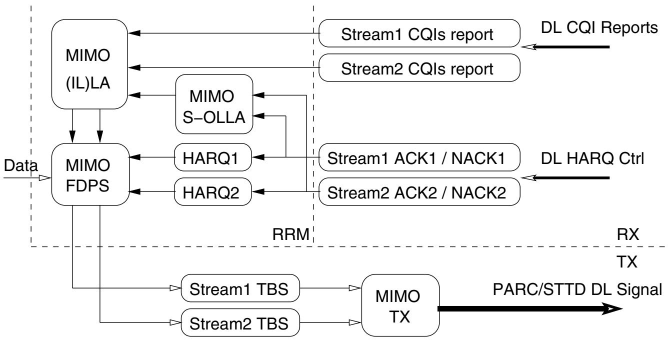

Fig. 1. Principles of the donwlink dual-stream MIMO LA/PS with CQI and Hybrid ARQ feedback information from terminals. Only the base station side is depicted.

As case study we are using a 2x2 MIMO transmission scheme with two operating modes: Per Antenna Rate Control (PARC) combined with Space-Time Transmit Diversity (STTD). The PARC transmission mode allows the dual-stream

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[1] The transmission scheme investigated here is single-user (SU) MIMO acoording to the defintion in [2]

transmission while the STTD mode is used as fall-back mode when the channel conditions are not favourable for PARC mode. The PARC uses two LMMSE receivers for the two independent streams. In Fig. 1, the CQI and the Hybrid ARQ (HARQ) ACK/NACK from the terminals are used as main input for the LA/PS. The LA/PS algorithm selects the scheduled terminals (time), allocates the corresponding resources (frequency) and selects the used modulation and coding scheme (MCS). The feedback of at least two CQI measures allows selection of independent MCS for the two data streams. Both PARC and STTD are open loop transmission modes, thus they do not require any additional information feedback from terminals. More complex MIMO schemes, where the single-stream and/or dual-stream modes are closed loop schemes, require the feedback of additional channel precoding or antenna weights information from the terminals, see e.g. [10], [11].

### *A. Outer loop link adaptation (OLLA)*

A single-stream OLLA algorithm, needed in order to meet the transmission BLER target, was proposed in [13], [14], [20]. Here we present an extension of this algorithm for dual-stream MIMO transmissions, MIMO-OLLA.

Firstly, the dual-stream MIMO-OLLA mechanism needs to utilize the separate CQI measures avalilable for the data streams. Secondly, the algorithm has to converge fast enough in order to provide adequate BLER control. Thirdly, the MIMO-OLLA operation can also be optimized based on the type of HARQ scheme used. In this paper we assume the less restrictive HARQ mechanism with two independent processes for the two data streams.

Similar to the single-stream OLLA algorithm described in [13], [14], [20], in our MIMO-OLLA scheme there are indepedent OLLA loops for every terminal served. The MIMO-OLLA offset ($A$) is updated only based on the received ACK/NACK feedback corresponding to a 1st transmission on either of the data streams and the current offset is substracted from the CQI (dB) reports received from the terminal.

With these assumptions, our proposed MIMO-OLLA scheme operates as one single OLLA loop (S-OLLA) and employs a single offset, $A$, which is used to control the average BLER on both data streams for each terminal. The offset updates are calculated as in Table I with the steps $A_{StepUp}$ and $A_{StepDown}$ based on the set BLER target, cf. Eq. (1). The initial value and the allowed range for the offset $A$ is set as described in [13], [14], [15].

TABLE I

PROPOSED MIMO *Single-OLLA* SCHEME WITH SINGLE CQI OFFSET CALCULATION ($NU$ = NOT A 1ST TRANSMISSION ACK/NACK).

| Received $ACK_x$/$NACK_x$ for 1st TX | Offset $A$ [dB] update |
|---|---|
| $ACK_1$ & $ACK_2$ | -$A_{StepDown}$ |
| $NACK_1$ & $NACK_2$ | +$A_{StepUp}$ |
| $ACK_1$ & $NACK_2$ or $NACK_1$ & $ACK_2$ | +$A_{StepUp}$ -$A_{StepDown}$ |
| $ACK_1$ & $NU_2$ or $NU_1$ & $ACK_2$ | -$A_{StepDown}$ |
| $NACK_1$ & $NU_2$ or $NU_1$ & $NACK_2$ | +$A_{StepUp}$ |

$$BLER = \left(1 + \frac{A_{StepUp}}{A_{StepDown}}\right)^{-1} \tag{1}$$

This S-OLLA algorithm can work with single or multiple (separate) HARQ processes for the transmitted streams. However, the same BLER target has to be used for both streams and for all transmission modes. When single-stream transmission mode is used, the S-OLLA operation simply defaults back to the basic OLLA.

From a system spectral efficiency point of view, the solution with *multiple* OLLA loops, one for each data stream, seems to be the optimal one. However, this solution also involves a significant signalling overhead and additional mechanisms to ensure that all OLLA loops active for one terminal are stable and converge. Therefore, it seems more reasonable to seek a simpler solution, especially when no additional 'quality' differentiation is needed between the transmitted data streams.

### *B. Fast inner loop link adaptation (ILLA)*

When a MIMO transmission scheme as described in Section II is operated, MIMO adaptation has to be also performed [19], [11], thus there is need for a mechanism to select between the two available MIMO transmission modes based on a certain system criteria. Here we have chosen to employ a MIMO adaptation based on the achievable total instantaneous throughput. The terminal determines one prefered single- or dual-stream transmission mode over the entire system bandwidth and feeds back this information to the base station (BS) along with the CQI reports. The LA/PS in the BS performs further MIMO adaptation based on the CQI reports and the actual PRB allocation for each terminal. With respect to the rate at which the MIMO mode adaptation is performed, we can distinguish between three main cases:

1) *Fast-adaptive*: with fast update rate, selected per each scheduling period (TTI) [11], [19] ,
2) *Quasi-adaptive*: with medium update rate (10 ms to 50 ms), selected only when a new (1st) transmission is to be scheduled on both streams and is kept the same during re-transmissions,
3) *Semi-adaptive*: with slow update rate (≈ 100ms) based on the average channel conditions [11], [19].

While the *Fast-adaptive* MIMO clearly offers the highest spectral efficiency it also requires the largest amount of DL signalling compared to the other two options [19]. The *Semi-adaptive* MIMO is only well suited for scenarios where the channel conditions are likely to change slowly in time, e.g. pedestrian, indoor, etc.. Based on these observations, we have chosen to operate with a *Quasi-adaptive* MIMO scheme, which can be used in both medium and low mobility scenarios and can yield a good trade-off between the DL signalling overhead and MIMO performances.

### *C. Frequency-domain packet scheduling (FDPS)*

A HARQ aware FDPS mechanism [14] extended to MIMO operation, with proportional fair (PF) scheduling in time and frequency domain was used. The time domain PS selects the maximum number of allowed frequency division multiplexed

($FDM$) terminals in each TTI, based on the full bandwidth PF metric and the selected MIMO mode (see Section II-B). The frequency domain PS first reserves the PRBs for the scheduled terminals with pending re-transmission (on either of the streams) from the total available system PRBs. In the second step, the actual allocation of the remaining PRBs to each terminal $u$ with scheduled 1st transmision is performed using the dual-stream PF metric, $PF_{u,n}^{DS}$, calculated based on the maximum instantaneously supported throughput between the single-stream, $D_{u,n}^{SS}$, and dual-stream, $D_{u,n}^{DS}$, transmission modes:

$$PF_{u,n}^{DS} = \frac{max\left(D_{u,n}^{SS}, D_{u,n}^{DS}\right)}{T_u} \tag{2}$$

where $n$ is the PRB index and $T_u$ is the average delivered throughput to the terminal in the past. In Eq. (2) the condition $D_{u,n}^{SS} \leq D_{u,n}^{DS}$ generally occures in high average SINR channel conditions ($\geq$10dB) when the use of spatial multplexing transmssion is more advantageous compared to diversity transmission [19], [11]. The terminals selected for scheduling and multiplexed in each TTI do not necessarily use the same MIMO mode. In the last step, the allocation of the PRBs to each terminal $v$ with scheduled re-transmission is performed based on the $PF_{v,n}^{DS}$ metric. All re-transmissions for a given terminal are scheduled on the same number of PRBs as the corresponding 1st transmission and using the same MCS (adaptive HARQ).

In this MIMO FDPS scheme, the PS/LA at the BS also performs MIMO mode adaptation based on Eq. (2). In practice this is possible only if either full CQI reports are available for both MIMO modes or when the CQIs for a given MIMO mode can be estimated from the CQI values corresponding to the other MIMO mode. For a 2x2 PARC/STTD MIMO scheme as analyzed in this paper the latter solution can be used in practical implementations.

## III. CHANNEL FEEDBACK SCHEMES

### A. Full CQI scheme

The CQI determined by the terminal based on pilot measurements are transmitted to the BS in a quantized form [2], [17], [20]. Here we assume that one CQI measure, including normally distributed measurement errors with $\sigma_{cqi}$ = 1.0 dB, corresponds to a bandwidth of $\Delta f_{cqi}$ = 360 kHz (2xPRBs granularity). The CQIs are formatted and quantized on $b_{CQI}$ = 5 bits, including $\Delta_{cqi}$ = 1.0 dB quantization errors. These CQI reports are then ready for use at the BS with a time-delay, $T_{delay}$, including both the time it takes to send the reports and the time to decode them at the serving BS. Here we assume that the CQI reports are always received correctly at the serving BS. The CQI reporting period ($T_{cqi}$) depends on the implementation solution and the desired accuracy for the CQI information for a given average channel condition.

In our case study, in a 9 MHz effective system bandwidth $K = 9000/\Delta f_{cqi} = 25$ reporting sub-bands are available. For the dual-stream MIMO transmission, when all $N_{CQI}$ = 3 CQIs: 2 CQI for dual-stream + 1 CQI for single-stream, are reported, the total required CQI feedback from one terminal per reporting period is $K \cdot N_{CQI} \cdot b_{CQI}$ = 375 bits. In the following, this case is referred to as *Full CQI* feedback case and is used as reference.

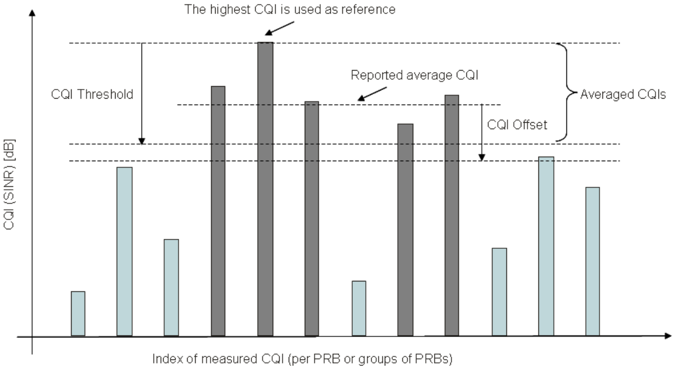

Fig. 2. Principles of the *Threshold based CQI* reporting scheme.

### B. Reduced CQI schemes

For a dual-stream transmission we have the option of using only $N_{CQI}$ = 2 CQIs corresponding to the maximum two possible streams instead of $N_{CQI}$ = 3 CQIs if the BS can estimate the single-stream CQI from the dual-stream CQI values. Furthermore, a simple procedure to reduce the feedback overhead is to report the absolute CQI with 5 bits only for one stream and the relative CQI for the other stream with e.g. 3 bits. Nevertheless, more significant feedback reduction is possible with the two reporting schemes presented in the following.

Two particular CQI feedback overhead reduction schemes are studied in this work: *Best-M CQI*, and *Threshold based CQI*. These two schemes have been investigated previously only for single-stream SIMO transmissions in Macro Cell scneario and were found to provide an acceptable trade-off from a cell throughput point of view [20]. In [20] it was shown that by using the *Threshold based CQI* for a 76% CQI feedback reduction it is possible to obtain only 4-8% cell throughput loss relative to the *Full CQI* feedback case.

The *Threshold based CQI* scheme provides a compression of the *Full CQI* information as presented in Fig. 2. Based on the measured CQIs, an average CQI value is computed of the CQIs that are included within a threshold limit relative to the highest measured CQI. A quantized version of the average CQI is reported together with a bit mask indicating the groups of PRBs included in the averaging. The bit mask is $K$=25 bits in this study. The CQI values for the the PRB blocks not selected (complementary set) of PRBs are set at the BS to a value which is CQI $Offset$ (dB) below the reported average CQI value.

In the *Best-M CQI* scheme the best $M$ group of PRBs are selected based on the measured CQIs and we also need the bit mask of $K$=25 bits indicating the selection [2]. The quantized version of the CQIs for each of the best $M$ groups of PRBs are reported. In our scheme, the complementary set of CQIs is not included in the feedback and they are simply set at the BS to the lowest CQI value in the reported best $M$ set.

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[2] In this case it is possible to compress the number of bits required for the mask by using an additional $log_2()$ compression [20].

TABLE II

CQI FEEDBACK SCHEMES AND ESTIMATED SIGNALLING BITS FOR $K$=25 SUB-BAND CQI REPORTS ($b_{CQI}$ = 5 BITS, $M$ = 10).

| CQI report | Expression | SISO/SIMO $N_{CQI}$=1 | MIMO $N_{CQI}$=3 |
|---|---|---|---|
| Full | $b_{CQI} \cdot N_{CQI} \cdot K$ | 125 | 375 |
| Best-M | $b_{CQI} \cdot N_{CQI} \cdot M + K$ | 75 | 175 |
| Threshold | $b_{CQI} \cdot N_{CQI} + K$ | 30 | 40 |

The BS configures the CQI $Threshold$, $Offset$ or $M$ parameters to be used. The two CQI reporting schemes described above have been adapted and evaluated for the MIMO PARC/STTD transmission with the following modeling assumptions:

- A common bit mask of $K$ bits (1 bit per reported sub-band) is used for all MIMO modes; the selection of the best-M PRBs at the terminal side is based on the single-stream CQI values only,
- The reduced CQI schemes are applied independently for each stream, and
- The measurement and quantization errors for all CQI values are modelled as being *fully independent*.

With these assumptions, Table II lists the number of required CQI feedback bits at each reporting period for the two schemes.

## IV. SYSTEM SIMULATION METHODOLOGY

Detailed multi-cell system-level simulations have been used in order to evaluate the performance of the presented S-OLLA, MIMO LA/PS (Section II) and reduced CQI reporting schemes (Section III). Table III lists the main simulation parameters and assumptions used in coherence with the main UTRAN LTE specifications [2]. LTE Macro Cell case #1 and LTE Micro Cell (outdoor-to-indoor) scenarios with frequency reuse 1 have been evaluated. All terminals in a cell are assumed to be active. The dual-stream CQI values take the inter-stream interference inherent for PARC transmission with two LMMSE receivers into consideration. The interfering cells are assumed to operate at full load and the interference at the terminal is calculated based on interfering STTD transmissions.

## V. PERFORMANCE RESULTS AND DISCUSSIONS

### A. Outer loop LA

The S-OLLA algorithm performances versus CQI measurement/estimation errors ($\sigma_{cqi}$) are summarized in Fig. 3, where we also compare the MIMO results with the SIMO transmission case in Macro Cell case #1 scenario. We can observe that this PARC/STTD MIMO scheme is slightly more sensitive to the large CQI errors compared to the SIMO case. This can be explained with the per-stream LA/HARQ mechanism used in the MIMO scheme where CQI errors can affect both streams simultaneously. Another important observation is that at low CQI errors ($\leq$ 1 dB) the extra degree of freedom in the LA - the MIMO adaptation - can partially mitigate the negative effects of noisy CQI reports even when OLLA is not activated. The difference between the performances in Macro and Micro Cell scenarios are due to the significantly different range of CQI values and the limited LA dynamic range.

TABLE III

SYSTEM-LEVEL SIMULATION PARAMETERS FOR DL UTRAN LTE.

| | |
|---|---|
| Carrier frequency | 2 GHz |
| Transmission bandwidth | 10 MHz |
| Number of active sub-carriers | 600 |
| Sub-carrier spacing | 15 kHz |
| Cellular scenario | Macro cell case #1, Micro cell<br>Hexagonal 19-site layout |
| Channel model | Typical Urban, 20 taps |
| Sub-frame duration | 0.5 ms (=simulation step) |
| Sub-carriers per PRB | 12 |
| Modulation schemes | QPSK, 16QAM, 64QAM |
| Hybrid ARQ | 6 process, CC, max 4 trans. |
| Link-to-system mapping | EESM |
| Number of terminals per cell | 20 (user diversity order) |
| Base station transmitter | 2-Tx PARC and STTD |
| Terminal receiver | 2-Rx LMMSE and MRC |
| Terminal noise figure | 9 dB |
| Terminal velocity | 3 kmph |
| Traffic model | Best effort, 4 Mbits payload |
| MIMO FDPS | PF in time and frequency<br>$FDM$ = 6,10 |
| S-OLLA | $BLER$ target = 20 %<br>$A_{StepUp}$= 0.5 dB<br>$A$ [-3,+5] dB range |
| CQI modelling | Quantization $\Delta_{cqi}$=1.0 dB<br>STD meas. error $\sigma_{cqi}$=1.0 dB<br>Meas. sub-band $\Delta f_{cqi}$=360 kHz<br>Reporting interval $T_{cqi}$=0.5 ms<br>Uplink delay $T_{delay}$=4 ms |
| CQI scheme | Best-M $M$ = 2:2:10<br>$Threshold$ = 1:1:6 dB<br>$Offset$ = 5 dB |

### B. Reduced CQI feedback

Fig. 4 shows the relative cell throughput losses when the reduced CQI schemes are used with PARC/STTD transmission. From these results we can conclude that we can achieve a 90% reduction for the required CQI feedback with the *Threshold based CQI* scheme while the cell throughput losses are kept below 10% if we use a $Threshold$ =4 to 5 dB, in both Macro and Micro cell scenarios. The *Best-M CQI* scheme generally yields higher losses compared to the *Threshold based CQI* scheme due to the independent errors affecting the reports in the best $M$ set of PRBs.

The general trend of the curves in Fig. 4 can be explained as follows; for low $Threshold$ or $M$ values, only a few blocks of PRB are included, while very high threshold values lead to the opposite case where most of the PRB blocks are included but averaged. Thus the knowledge of the channel frequency diversity is lost.

The performance losses from using either of these CQI feedback schemes in PARC/STTD transmission is generally higher when more terminals are frequency multiplexed per TTI, higher $FDM$. This observation is in contrast to the results obtained with single-stream SIMO transmission scheme reported in [20]. This can be explained with the multi-

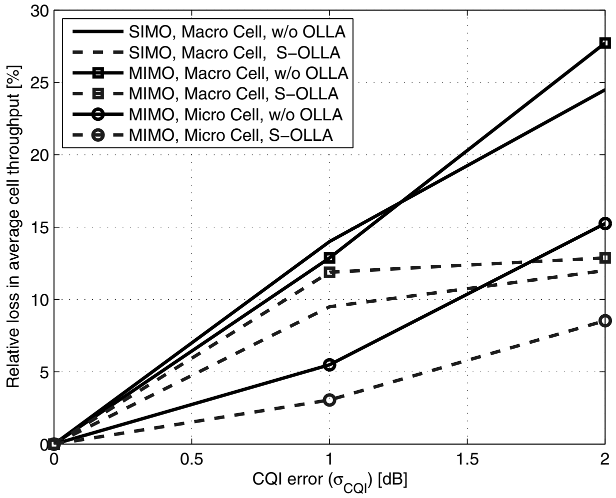

Fig. 3. Relative loss in cell throughput versus the CQI measurement error ($\sigma_{cqi}$) for MIMO PARC/STTD transmission. *Full CQI* scheme was used.

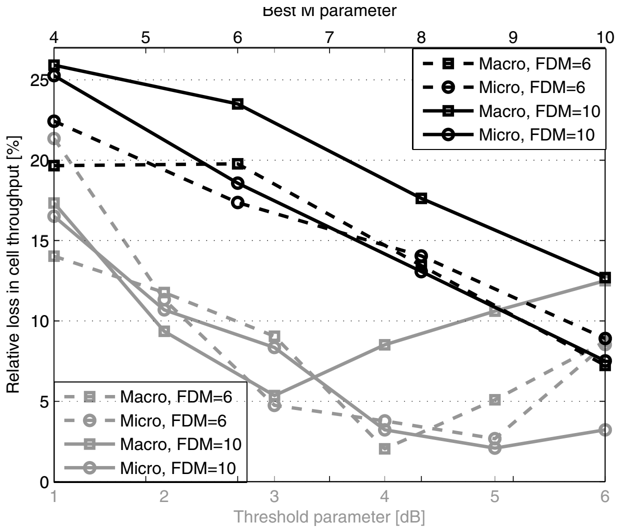

Fig. 4. Relative performance loss in average cell throughput from using *Best-M CQI* (upper axis) and *Threshold based CQI* (lower axis) reporting schemes as compared to the *Full CQI* scheme ($\sigma_{cqi}$=1.0 dB).

user diversity gain of approximately 10% when $FDM$=10 compared to $FDM$=6 case in the reference scheme, and this gain is gradually vanishing with reduced CQI for increasing $M$ or $Threshold$ parameter values.

## VI. CONCLUSIONS

In this paper we have analyzed the system-level performances of a 2x2 dual-stream PARC/STTD MIMO OFDMA transmission scheme under the assumptions of partial and noisy CQI feedback available from the terminals. The CQI feedback effects in terms of terminal measurement and estimation errors, quantization errors, uplink reporting format and delays are included. Two reduced CQI reporting schemes, *Best-M CQI* and *Threshold based CQI*, have been extended for MIMO and evaluated in combination with a proposed MIMO-OLLA and a MIMO aware FDPS algorithm. We showed that with the *Threshold based CQI* scheme the required CQI feedback overhead can be reduced by 90% while limiting the cell throughput losses to less than 10%. As a continuation of this work, performance evaluation of higher order MIMO transmission schemes with limited and non-ideal channel feedback will be performed in future studies.

## ACKNOWLEDGMENT

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