

Performance of MIMO Aware RRM in Downlink OFDMA

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Abstract — This paper addresses advanced radio resource management (RRM) algorithms for multiple-input multiple-output (MIMO) transmission schemes in downlink OFDMA systems. The analysis covers the main RRM mechanisms including MIMO rank adaptation and time-frequency packet scheduling. The UTRAN Long Term Evolution (LTE) system is used as case study. System-level performance analysis is presented for 2x2 and 4x4 spatial-multiplexing, single-user MIMO transmission schemes in typical Macro- and Micro-Cell scenarios including the effects of limited and imperfect CQI feedback from the terminals. We show that time-frequency domain RRM schemes can be successfully adapted and optimized for operations with high-rate adaptive MIMO transmission schemes.

I. INTRODUCTION

MIMO OFDMA based cellular systems are currently being standardized by 3GPP for UTRAN LTE [1][2][3], and by IEEE for WiMAX [4], with first releases planned to be available by mid 2008. In parallel, several research projects e.g. WINNER [5], MASCOT [6], SURFACE [7], are investigating advanced MIMO OFDMA transmission schemes for operating bandwidths of up to 100 MHz.

This paper proposes and evaluates design solutions for MIMO-aware radio resource management (RRM) algorithms for downlink OFDMA systems covering Hybrid Automatic Repeat Request (HARQ), link adaptation (LA), MIMO rank adaptation and time-frequency packet scheduling algorithms. The UTRAN LTE system with frequency-domain localized downlink transmission is used as a case study, and the 2x2 and 4x4 MIMO transmission schemes with spatial-multiplexing (SM) are the main focus of the work presented herein. The previously published RRM solutions for WCDMA, e.g. in [9][10], and LTE, e.g. in [1][8][13][14], are used as starting point for this work. The proposed RRM solution for a practical open-loop (OL) dual-stream MIMO scheme presented in [15] is extended in this work to accommodate also closed-loop (CL) spatial-multiplexing (SM) MIMO schemes employing the 3GPP precoding mechanisms [3]. Typical Macro- and Micro-Cell scenarios [2] are chosen for extensive multi-user system level evaluation. Limitations due to practical LTE OFDMA system design aspects are considered, including the channel estimation errors, channel quality indicator (CQI) imperfections and uplink feedback delays [3][13][14].

The paper is structured as follows. Section II describes the main RRM blocks, their functionality and related modeling aspects. In Section III the system-level simulation assumptions are presented. Section IV presents the discussions of the

results for representative RRM settings in combination with several transmission schemes. The main conclusions from this study are summarized in Section V.

II. SYSTEM AND ALGORITHM CONSIDERATIONS

A. Overall RRM description

Fig. 1 shows the block diagram of the MIMO-aware RRM functionalities analyzed and modeled in this paper. Here we address only the RRM mechanisms for the downlink shared data channel. Section II.B– II.G describe in detail the functionalities and the assumptions used in this study. The minimum frequency-domain scheduling granularity is defined as one Physical Resource Block (PRB) and consists of a group of 12 consecutive OFDM subcarriers [3]. The minimum time-domain scheduling granularity is a transmission time interval (TTI) of 1 ms duration and contains of 14 OFDM symbols out of which 3 symbols are used for control channel data [3].

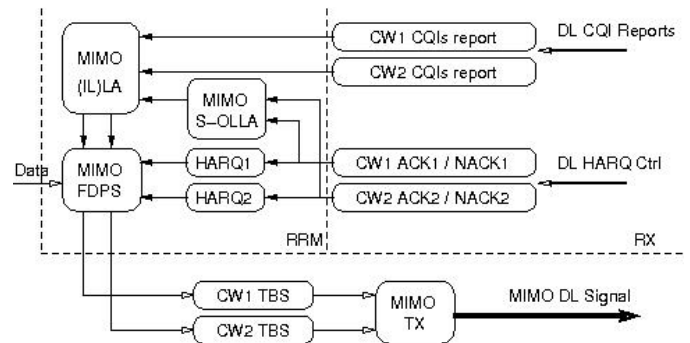


Fig. 1. The block diagram of the analyzed downlink MIMO-aware RRM. Only the base station side is depicted. Multi-stream MIMO feedback is considered to be included in the CQI reports from terminals.

Several PRBs can be allocated/ scheduled simultaneously for the transmission to a terminal and the allocation is performed dynamically on a per-TTI basis at the BS side. An important LTE system related assumption used herein is the use the same modulation and coding scheme over all the PRBs allocated to one user in one transmission [3].

B. MIMO schemes

Table I lists the MIMO transmission scheme investigated in this study and the terminology used. The MIMO rank identifies the number of spatial streams while the MIMO codeword is used to jointly encode up to two spatial streams. In the context of this work the closed-loop MIMO operation is implemented using codebook based pre-coding, i.e. the

TABLE I
MIMO CODEBOOK SIZES USED AND SPATIAL STREAM TO CODEWORD MAPPING
FOR THE SELECTED MIMO SCHEMES

	Rank 1	Rank 2	Rank 3	Rank 4
MIMO 2x2	6 vectors	3 matrices	No	No
MIMO 4x4	16 vectors	16 matrices	16 matrices	16 matrices
Codeword #1	Stream #1	Stream #1	Stream #1	Stream #1
Codeword #2	-	Stream #2	Stream #2	Stream #3
			Stream #3	Stream #4

antenna weights (vector or matrix) to be applied at the BS side are selected from a fixed number of possibilities, forming a quantized codebook set [3]. Furthermore, for all the SM MIMO schemes investigated in this work we assume that the multiplexed spatial streams are transmitted to the same terminal. These assumptions correspond to the single-user MIMO schemes in the 3GPP LTE terminology and the codebooks are specified in [3]. The codebook sizes are also summarized in Table I.

C. MIMO feedback from terminals

The minimum required feedback from the terminals for performing the downlink RRM at the BS comprises:

1. Channel state/quality information (CQI): direct (e.g. SINR) or indirect (e.g. MCS) information on the average channel conditions estimated on the physical resources and MIMO spatial streams,
2. MIMO information: indicates the optimum number spatial streams to be used (MIMO rank) and the corresponding pre-coding vector/matrix index (PMI), and
3. HARQ information: indicates the reception status (ACKnowledged / Not ACKnowledged) of the transmitted data packets on the scheduled MIMO spatial streams.

The first two items above, CQI and PMI, are determined by the terminal based on pilot measurements and are transmitted to the BS in a quantized form. The accuracy of both CQI and PMI is dependent on several system design choices, such as time-frequency pilot distributions, channel estimation and advanced receiver algorithms, etc. These accuracy aspects are not studied in this paper. The HARQ scheme and related feedback are addressed in Section II.E.

1) Channel quality feedback

Here we assume that one CQI measure represents the average SINR estimate, including normally distributed measurement errors with 1.0 dB, corresponding to a bandwidth of 360 kHz (2xPRBs granularity). The CQIs are formatted and quantized on 5 bits, including 1.0 dB quantization errors [13][14]. These CQI reports are then ready for use at the BS with a time-delay of 2.0 ms (2 TTI), including both the time it takes to send the reports and the time to decode them at the BS. We further assume that the CQI reports are always received correctly at the serving BS. A periodic CQI reporting scheme with a period of 5.0 ms (5 TTI) is considered as a base-line case [13][14]. In theory the optimal link adaptation operation with SM MIMO schemes requires separate CQI measures estimated for each separately encoded spatial stream. Without significant

loss of performance in LTE the CQI feedback has been reduced by grouping the spatial streams in 2 groups with maximum 2 streams each, so that two CQI measures are sufficient for the considered MIMO transmission schemes [3]. Each group of streams is separately encoded and corresponds to one codeword, see Table I. This choice of using two codewords influences also the HARQ mechanisms as described in Section II.E.

2) Closed-loop MIMO feedback

Based on the instantaneous channel conditions the terminal has to estimate the optimum MIMO rank, and the corresponding optimum pre-coding vector(s)/matrix(ces). Ideally, both the MIMO rank, and the PMI should be estimated for each PRB, i.e. assuming frequency-selective MIMO adaptation. For large system bandwidths of 5 MHz and above, in practice this approach leads to a very large signaling overhead introduced in the uplink. A good compromise can be achieved by using MIMO feedback per groups of several consecutive PRBs. This approach is further motivated by the choice made for the CQI feedback in LTE systems as described in Section II.C.1. The MIMO feedback information is transmitted on an uplink channel to the serving BS together with, or embedded in, the CQI reports [3]. In our study we assume that all MIMO related feedback is error free and it is subject to the same delay 2.0 ms as the CQI reports.

D. Link and MIMO Rank Adaptation

The optimized operation of the MIMO transmission schemes introduced in Section II.B requires, in addition to the classical link adaptation (selection of the optimal MCS / TBS), a MIMO rank adaptation mechanism.

Here we have chosen a straightforward and simple scheme: The optimum MIMO rank is selected at the terminal side to *maximize the user throughput*. However, when CL MIMO schemes are used, for this MIMO rank selection procedure a certain pre-coding vector/matrix has to be pre-determined or assumed in order to estimate the achievable total throughput with each possible rank. The optimum pre-coding vector/matrix can be determined based on various PHY/MAC criteria: *maximum beam-forming gain*, *maximum SINR* or *maximum throughput*. For this study we have chosen to use the first criterion as it is simple and it implies the computation of signal power levels only. The latter ones are more complex and require information about the number of allocated PRBs, the interference levels and/ or potentially even the MCS used.

In the context of the LTE system, because the same modulation and coding scheme is used on all the allocated PRBs, it is also reasonable to assume that the same MIMO rank can be used for all the allocated PRBs. Furthermore, given that the actual PRB allocation is determined by the PS in the BS and not at the terminal side, we choose as practical solution to use one single MIMO rank determined for the entire monitored system bandwidth, i.e. for all PRBs.

The frequency granularity of the PMI feedback can, however, be different from the MIMO rank. In this study we assume two reference PMI selection schemes combined with the above described full-bandwidth MIMO rank selection:

1. *Frequency non-selective PMI*: one PMI is determined for the entire effective system bandwidth and,
2. *Frequency selective PMI*: one PMI is determined for each group of 2 consecutive PRBs, i.e. using the same 2xPRB granularity as the CQI measures.

Using the MIMO and CQI feedback information from all the active terminals in the serving cell, the RRM algorithm in the serving BS performs the actual resource allocation and scheduling for each terminal. Previous investigations with low mobility MS scenarios have disclosed the influence on the overall system performance of the rate at which the MIMO adaptation is performed, e.g. [9][12]. The results show that a semi-adaptive scheme with slow update rate (~100 ms) based on the average channel conditions yields only small cell throughput losses in order of 5 % compared to the case with a *fast-adaptive* scheme with MIMO rank selected in each scheduling period. Here we analyze two reference schemes:

1. *G-factor based (GF)*: with rank update based on the average wideband channel SINR conditions (see e.g. [9][12]) and,
2. *Quasi-dynamic (QD)*: with rank selected only when a new (1st HARQ) transmission is scheduled (see e.g. [15]).

The *quasi-dynamic* MIMO scheme [15], is a trade-off solution between the *fast-adaptive* (per TTI) and the *G-factor based* (per 5ms to 10 ms) schemes, and can be used in both medium and low mobility scenarios, thus yielding a good trade-off between the DL signaling overhead and MIMO performances. It has to be noted, that in our study the MIMO rank adaptivity implies only the rank selection and not the precoding vector/matrix selection. Thus, after the selection of a given transmission rank, the optimum pre-coding is updated based on the current channel conditions.

E. HARQ schemes

Our basic assumption is the use of a HARQ chain with 6 asynchronous Stop And Waits (SAW) processes [3]. The HARQ mechanism for a multi-stream MIMO transmission has to handle the individual spatial streams. Assuming the spatial stream grouping as explained in Section II.C.1, we have selected a rather optimal MIMO HARQ mechanism, *Dual HARQ*, with independent HARQ chains for each codeword. There is no HARQ process synchronization between the two HARQ chains and two separate ACK/NACK signaling is required from the terminal. From spectral efficiency point of view this is the optimal solution because the codewords are handled completely independently as two separate transmissions.

F. Outer Loop Link Adaptation

In previous studies an Outer Loop Link Adaptation (OLLA) has been shown to provide a good mitigation mechanism for the LA errors caused by the imperfect CQI feedback information [13][14][15]. Our proposed OLLA scheme for multi-stream MIMO operates as one single OLLA loop (S-OLLA) and employs a single offset, which controls the

average BLER (over both codewords) for each terminal separately; the details are described in [15].

G. Packet Scheduling

A HARQ aware time-frequency domain packet scheduling (FDPS) mechanism [13][14] extended to operate with spatial-multiplexing MIMO schemes was proposed in [15]. The proportional fair scheduling metric is used in both the time and frequency domain PS. However, opposed to the solution described previously in [15], here we restrict the RRM in the BS so that it *cannot* change the MIMO rank selected at the terminals. We consider this as being a more practical operating scheme based on the limited information feedback available from the terminals, see Section II.C.

III. SYSTEM-LEVEL SIMULATION

A. General settings

In order to evaluate the performance of the presented MIMO-aware RRM algorithms and transmission schemes, detailed system-level multi-cell simulations have been carried out. Table II lists the main simulation parameters and assumptions used. The 3GPP Macro Cell case #1 and LTE Micro Cell (outdoor-to-indoor) scenarios in a frequency reuse 1 network have been evaluated [1][2]. All terminals in a cell are assumed to be active, have low mobility (3 kmph) and utilize the same type of MIMO transmission scheme. The interfering cells are assumed to operate at full load and the interference signal at the receiving terminal is calculated based on the assumption that it originates from a MIMO Rank 1 transmissions with the same number of transmit antenna ports. The (self) inter-stream interference at the receiver is explicitly calculated when estimating the SINR and CQI measures at the output of the LMMSE receivers. The 3GPP SCM MIMO-correlated channel model has been used [2].

B. RRM settings and scenarios

Based on the discussion in Section II, Table III summarizes the RRM options considered in this study. The performance of these RRM schemes has been evaluated in combination with the two adaptive MIMO transmission schemes listed in Table I, in terms of average cell spectral efficiency (SE) and cell-edge user (coverage at 5% outage) spectral efficiency.

IV. RESULTS AND DISCUSSIONS

For this analysis we use the quasi-adaptive MIMO and the dual-HARQ mechanism. Figure 2 and Figure 4 show the performance results for the two selected MIMO rank adaptation schemes (see Table III) in Macro- and Micro-Cell scenarios, respectively. Moreover, in Figure 3 and Figure 5 the corresponding rank distributions are presented.

As indicated in Table I, maximum transmission rank for 4x4 MIMO (4) is double the maximum transmission rank of 2x2 MIMO (2). This together with 3 dB array gain and additional degrees of freedom in rank adaptation that 4x4 MIMO is having over 2x2 MIMO imply that 4x4 MIMO

TABLE II
SYSTEM SIMULATION PARAMETERS

Parameter	Setting/Value
Carrier frequency	2 GHz
Transmission bandwidth	10 MHz
Number of active sub-carriers	600
Cellular scenario	3GPP Macro Cell case #1 and Micro Cell LTE [2]
Number of terminals per cell	20
Channel model	3GPP SCM correlated type
Sub-frame duration	1 ms
Sub-carriers per PRB	12 sub-carriers = 180 kHz
Modulation schemes	QPSK, 16QAM, 64QAM
Hybrid ARQ	6 SAW processes per codeword
Link-to-system mapping	EESM
Base station transmitter	2 or 4 antenna elements
Terminal receiver	2 or 4 antenna elements MRC or LMMSE per codeword
Terminal noise figure	9 dB
Terminal velocity	3 kmph
Traffic model	Infinite queue/buffer
MIMO RRM	Time-frequency packet scheduling. UE-side MIMO rank adaptation.
CQI model	2xPRBs resolution. Includes measurement errors, quantization, delays and reporting period[13][14]
Closed-Loop MIMO feedback model	Error-free. Code-book based.

TABLE III
ANALYZED MIMO RRM SETTINGS (SEE DETAILS IN SECTION II)

Parameter	Setting/Value
TD-FD PS	Time-frequency domain proportional fair scheduling, with max 10 users per TTI
MIMO schemes	Adaptive 2x2 and 4x4 [3].
MIMO rank adaptation	G-Factor based (GF) Quasi-dynamic (QD)
CL MIMO feedback	Frequency selective (FS): 2xPRBs Frequency non-selective (FNS): Full-bandwidth (all PRBs)

scheme shows a performance increase in the order of 50% to 60% for both average cell and cell-edge SE measures over the 2x2 MIMO scheme. The relative gain of the 4x4 MIMO scheme can be achieved in both Macro and Micro cellular environments.

A. MIMO adaptation rate

In the Macro-Cell scenario for 2x2 MIMO, regardless of the PMI feedback mechanism used, the G-factor based rank adaptation yields 10 % loss in the average cell throughput. The coverage performance is more significantly impacted by the slow rank adaptation rate and 10 % to 15 % losses can be observed depending also on the PMI feedback scheme. This loss can be explained by the fact that G factor based rank adaptation tends to favor higher transmission ranks compared to quasi-adaptive transmission scheme (see Figures 3 and 5). This implies more transmission errors and re-transmissions for the cell-edge users due to non-ideal rank selection. By using frequency non-selective PMI the impact of non-ideal rank selection can be compensated.

In the Micro-Cell scenario, due to the propagation conditions with higher probability of good SINR values the probability to use transmission rank 1 is decreased, and hence the impact of the G-factor based rank adaptation is reduced compared to the Macro-Cell scenario. Thus, only a 3% loss in the average cell throughput is obtained, while the cell-edge performance is reduced by 5 %.

For the 4x4 MIMO scheme the impact of different rank adaptation rates is very similar to 2x2 MIMO, but due the additional degrees of freedom available in the rank adaptation this impact is less significant and decreases further when frequency non-selective PMI is used.

B. CL MIMO feedback schemes

The Macro-Cell results for the 2x2 MIMO schemes, show a loss of 5 % in cell-edge user performance and only a minimal loss (1 %) for the average cell throughput when the frequency non-selective PMI feedback is utilized in the MIMO adaptation mechanism. The Micro-Cell results show similar results for the cell-edge performance while the average cell performance is practically not impacted by the PMI feedback mechanism due to better average channel conditions over the entire system bandwidth.

With the 4x4 MIMO scheme, the macro cell results show higher loss in cell-edge user performance (10 %) and for the average cell throughput (5 %) compared to the 2x2 MIMO scheme. This can be explained by the higher impact of the reduced frequency granularity of the PMI is having for 4x4 MIMO. In the Micro-Cell scenario similar conclusions hold than for 2x2 MIMO scheme, even though the relative losses in the cell-edge user performance and for the average cell throughput are slightly higher than for 2x2 MIMO scheme.

For the case when the MIMO rank is adapted quasi-dynamically, the results in Figure 3 and Figure 5 show an increase in the use of higher rank transmissions with frequency non-selective PMI compared to the frequency selective PMI case. This indicates an overestimation of the quality of the supported transmission when frequency non-selective PMI is used, and similar to the observation in Section IV.A, this results in penalty in the achieved performance.

V. CONCLUSION

In this paper we have evaluated the system performance of several practical spatial-multiplexing 2x2 and 4x4 MIMO OFDMA transmission schemes in typical Macro- and Micro-Cell scenarios utilizing limited and imperfect channel feedback from the terminals. Two main RRM mechanisms have been analyzed: MIMO rank adaptation, and MIMO precoding information feedback. For both the 2x2 and 4x4 MIMO transmission schemes, the Macro-Cell investigations show gains in the average cell spectral efficiency and the cell-edge spectral efficiency in the order of 10 % and 18 %, respectively, when using quasi-dynamic MIMO rank adaptation and frequency selective closed-loop information feedback compared to the G-factor based and frequency non-selective case. The performance in Micro-Cell scenarios is less

impacted, with gains of up to 4% and 15 %, respectively. The latter results confirm the suitability and high potential of the downlink MIMO schemes in microcellular environments without introducing significant overhead in the uplink signaling and control channels payload.

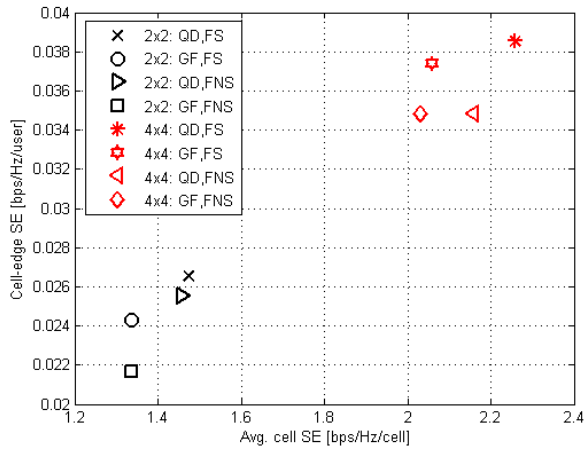


Fig. 2 Average cell SE vs. and cell-edge user (coverage) SE performance for MIMO schemes operating in the Macro-Cell scenario.

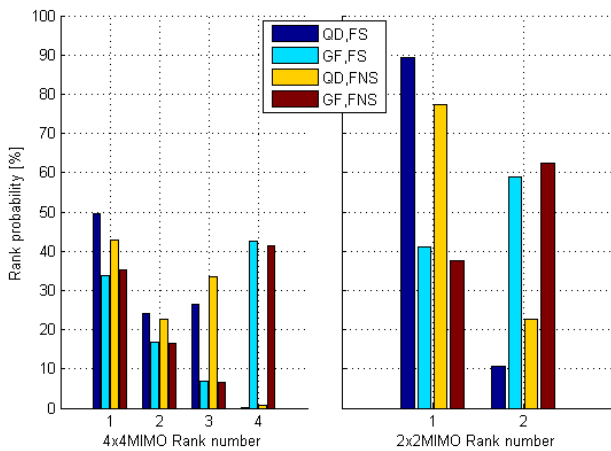


Fig. 3 Rank distributions for different MIMO rank adaptation rates and PMI feedback schemes in the Macro-Cell scenario.

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REFERENCES

- [1] A. H. Ekstrom et al., "Technical Solutions for 3G Long Term Evolution," *IEEE Comm. Mag.*, vol. 44, no. 4, pp. 38–45, Mar. 2006.
- [2] 3rd Generation Partnership Project; Technical Specification Group Radio Access Network, "Physical Layer Aspects for Evolved UTRA (Release 7), 3GPP TR25.814, v7.1.0," Tech. Rep., Sept. 2006.
- [3] 3rd Generation Partnership Project; Technical Specification Group Radio Access Network, "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation (Release 8), 3GPP TS36.211, v8.1.0," Tech. Spec., Nov. 2007.
- [4] WiMAX Forum™, www.wimaxforum.org, Tech. Rep., Aug. 2006.
- [5] "Wireless World Initiative New Radio (WINNER)," IST-507581, European Information Society Technologies, Tech. Rep., Dec. 2006.

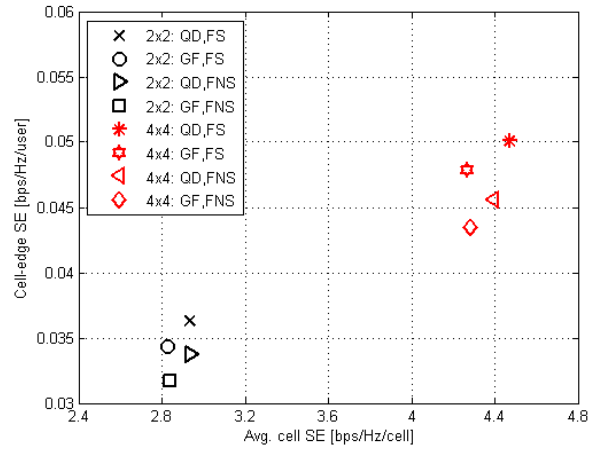


Fig. 4 Average cell SE vs. and cell-edge user (coverage) SE performance for MIMO schemes operating in the Micro-Cell scenario.

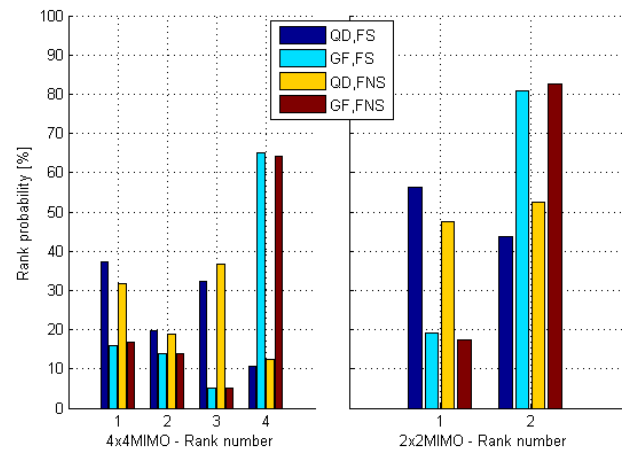


Fig. 5 Rank distributions for different MIMO rank adaptation rates and PMI feedback schemes in the Micro-Cell scenario.

- [6] "Multiple-Access Space-Time Coding Testbed (MASCOT)," IST-26905, European Information Society Technologies, Tech.Rep., Dec. 2006.
- [7] "Self Configurable Air Interface (SURFACE)," IST-027187, European Information Society Technologies, Tech. Rep., Jan.2006.
- [8] A. Pokhariyal et al., "Performance of Downlink Frequency Domain packet Scheduling for the UTRAN Long Term Evolution," in *Personal, Indoor and Mobile Radio Communications*, Sept. 2006.
- [9] E. Tuomaala et al., "Performance of Spatial Multiplexing in High Speed Downlink Packet Access System," *5th Intl. Conf. on Inf., Comm. and Signal Proc.*, Dec. 2005.
- [10] J. Peisa, et al., "High Speed Packet Access Evolution - Concept and Technologies," in *IEEE Proc. Veh. Technol. Conf.*, April 2007.
- [11] N. Wei et al., "Analysis and Evaluation of Link adaptation with MIMO adaptation," in *IEEE Proc. Veh. Technol. Conf.*, Sept. 2006.
- [12] N. Wei, et al., "Efficiency of Closed-Loop Transmit Diversity with limited feedback for UTRA Long Term Evolution," in *Personal, Indoor and Mobile Radio Communications*, Sept. 2006.
- [13] A. Pokhariyal et al., "HARQ Aware Frequency Domain Packet Scheduler with Different Degrees of Fairness for the UTRAN Long Term Evolution," in *IEEE Proc. Veh. Technol. Conf.*, May 2007.
- [14] K. I. Pedersen et al., "Frequency Domain Scheduling for OFDMA with Limited and Noisy Channel Feedback," in *IEEE Proc. Veh. Technol. Conf.*, Oct. 2007.
- [15] I.Z. Kovács et al, "Effects of Non-Ideal Channel Feedback on Dual-Stream MIMO OFDMA System Performance", in *IEEE Proc. Veh. Technol. Conf.*, Oct. 2007.