

# Feedback Design for Multi-User MIMO Systems

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**Abstract**—We consider feedback design for the integration of multi-user MIMO in cellular mobile radio systems. Feedback is given by the mobile terminals, which report beam indices referring to a set of fixed pre-coding beams and corresponding signal to signal to interference and noise ratio (SINR) for different supported spatial transmission modes. The SINR feedback is quantized with a different number of bits, and the performance in terms of throughput achieved with a score-based scheduler is evaluated. Test scenarios from multi-cell simulations as well as single-sector measurements are considered. Results show that cell-edge users benefit the most from an increased amount of feedback bits.

## I. INTRODUCTION

Spatial transmit mode selection is a key concept for multi-antenna communication systems. The elementary trade-off between diversity and multiplexing for these multiple-input multiple-output (MIMO) radio systems is described in [1]. The major task of the medium access layer (MAC layer) in a MIMO system is to operate the multi-antenna radio link in the right balance between diversity and multiplexing. Therefore, one observes the time- and frequency-selective channel and interference conditions at the terminal side and feeds this information back to the base station (BS) on a regular basis.

An early implementation of this idea is per antenna rate control (PARC). It adapts the rates on spatially multiplexed streams based on a small feedback rate such that the sum rate over all antennas is maximized [2]. It can be of great advantage to switch-off spatial streams, e.g. if the rank of the channel matrix is too low with a free line-of-sight. A higher capacity can then be realized with less data streams on air [3], i.e. by applying a more diversity-oriented transmission strategy. Both approaches use the effective signal to interference and noise ratio (SINR) at the output of the spatial signal processing at the receiver to estimate the achievable capacity and to optimize the radio link accordingly. In con-

trast, a measure for the channel rank is used to switch between diversity and multiplexing in [4].

A practical approach to multi-user MIMO, based on the effective SINR is presented in [5]. The original concept has been extended and examined in single- and multi-cell environments [6]–[10]. Implementation has been developed towards a functional real-time prototype realizing the essential physical and adaptive MIMO MAC layer mechanisms for cellular orthogonal frequency division multiplexing (OFDM) parameters close to the 3G Long Term Evolution (3G-LTE) standard [11]–[14]. Successful tests in cellular scenarios have recently been conducted [15]–[17].

In this paper, we investigate the impact of feedback quantization on the achievable spectral efficiency. Our results are based on SINRs generated in a multi-cell simulation environment as well as measured in a LTE testbed measurement campaign.

The MIMO-OFDM downlink model is described in section II. In section III-A, our multi-cell simulation environment is introduced. The measurement scenario is described in section III-B. Section IV summarizes the multi-user MIMO scheduling algorithms used in both cases. In section V we present our main results.

## II. SYSTEM CONCEPT FOR MIMO-OFDM

The downlink MIMO-OFDM transmission via  $N_T$  transmit and  $N_R$  receive antennas for each subcarrier is described by

$$\mathbf{y} = \mathbf{H}\mathbf{C}\mathbf{x} + \mathbf{n}, \quad (1)$$

where  $\mathbf{H}$  is the  $N_R \times N_T$  channel matrix and  $\mathbf{C}$  the unitary  $N_T \times N_R$  codebook matrix;  $\mathbf{x}$  denotes the  $N_T \times 1$  vector of transmit symbols;  $\mathbf{y}$  and  $\mathbf{n}$  denote the  $N_R \times 1$  vectors of the received signals and of the additive white Gaussian noise (AWGN) samples. In this work we consider  $N_T = N_R = 2$ .

The overall transmission concept is based on fixed pre-coding beams contained in  $\mathbf{C}$ . The physical

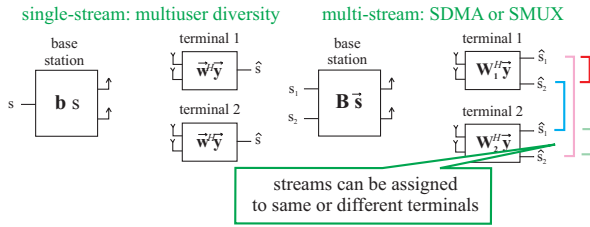


Fig. 1. Basic transmission modes in a multi-user MIMO system

layer has two principal modes: single-stream (ss) transmission for spatial diversity and multi-stream (ms) transmission for spatial multiplexing.

In ss mode, the effective post-equalization SINR is derived for a set of beam-forming vectors in the pre-defined codebook. The SINR value for the best beam and the index of this beam is fed back to the base station.

In ms mode, a suitable beam set is selected for spatial multiplexing (SMUX) transmission and the ultimate separation of the streams is done at the multi-antenna terminal. For a given set of unitary beam-forming matrices, the individual SINR is obtained for each spatially multiplexed stream. Stream rates for the beam-forming matrix yielding maximum sum rate and the corresponding matrix index are fed back.

The MIMO-MAC layer at the BS has three options, see Fig. 1. In ss mode, the terminal with the best rate may be selected to achieve multi-user diversity. In ms mode, streams may be assigned either to the same terminal, i.e. single-user MIMO (SU-MIMO), or to different terminals, i.e. multi-user MIMO (MU-MIMO). The striking advantage of this proposal is the high performance achieved with comparatively low amount of feedback: The BS enables MU-MIMO without having coherent channel state information. Only the SINR and codebook indices must be reported for ss and ms modes. The required feedback rate depends on the coherence bandwidth and the coherence time of the channel.

Transmission resources in the OFDM system are structured into resource blocks (RBs), which are defined over frequency and time as a block of consecutive subcarriers and OFDM symbols, respectively. In conjunction with the different beams offered by the BSs they form the scheduling resources which may be individually assigned to the users. An extended score-based scheduler [7], [18] known to asymptotically achieve proportional fairness, is used to switch adaptively between multi-user diversity and multi-user multiplexing mode in a frequency-

TABLE I  
SIMULATION ASSUMPTIONS.

Parameter	Value
channel model	3GPP SCME <sup>1</sup>
scenario	urban-macro
additional modifications	scenario-mix <sup>2</sup>
$f_c$	2 GHz
system bandwidth	31.72 MHz, 128 RBs
signal bandwidth	18 MHz
intersite distance	500m
number of BSs	19 having 3 sectors each
antenna elements ; spacing	2 ; $4\lambda$
transmit power	46 dBm
sectorization	triple, with FWHM <sup>3</sup> of $68^\circ$
BS height	32m
antenna elements ; spacing	2 ; $\lambda/2$
MT height	2m

selective manner. This decision is based on the channel quality identifier (CQI) feedback reported by the users.

#### A. CQI Feedback

The CQI feedback is calculated for each spatial mode at the mobile terminal (MT). The effective per beam SINRs are calculated for single- and dual-stream transmission and the logarithmic values are, for simplicity, uniformly quantized with  $b \in \{1, 2, 3, 4, 5, 6, \infty\}$  bit. The minimum value is truncated at  $-2$  dB, while the upper threshold is clipped at  $\{10, 16, 18, 20, 22, 24, 26\}$  dB with increasing number of bits.

### III. TESTCASES

#### A. Multi-cell Simulation Environment

Monte Carlo simulations are based on the 3GPP SCME channel model, with simulation assumptions given in Table I and some modifications, discussed in [8]. For the sectorization the simulation scenario is initialized cell-wise, i.e. independently for each BS. The large scale parameters are kept fixed for all 3 sectors belonging to the same BS while the small scale parameters are randomized as indicated in [19].

The MTs are always served by the BS whose signal is received with highest average power over

<sup>1</sup>Spatial Channel Model Extended.

<sup>2</sup>i.e. each cell, consisting of 3 sectors, may have different channel conditions, e.g. line of sight (LOS) or non line of sight (NLOS).

<sup>3</sup>full width at half maximum.

TABLE II  
DOWNLINK MIMO-OFDM TEST-BED PARAMETER SET

System Parameter	Value
Downlink band	2.68 GHz
Antennas BS/MT	2 Tx/Rx
Bandwidth used	up to 18 MHz
Symbol period	71.4 $\mu$ s
Cyclic prefix	4.7 $\mu$ s
Total # of sub-carriers	2048
# of used sub-carriers	1200
Radio frame duration	10 ms
Transmit-time interval (TTI)	0.5 ms
TTIs per radio frame	20
Symbols per TTI	7
Resource block size	25 sub-carriers
# of Resource blocks	48
Modulation	4-, 16-, 64-QAM
Channel coding rates	Convolutional with 1/2, 3/4
Feedback update rate	10 ms
Feedback granularity	3 RBs
BS transmit power	10 W
MT transmit power	200 mW

the entire frequency band and in each independent channel realization. For capacity evaluation only MTs being placed inside of the center cell will be considered, so that BS signals transmitted from 1st and 2nd tier model the inter-cell interference [8].

### B. Measurement Scenario

*Parameter Set:* The parameter set for the PHY implementation was chosen according to tentative working assumption issued around November 2005, which is shown in **Table II**. The system bandwidth was set to 20 MHz in the digital domain. The BS transmission power was set to 10 W and the MT transmission power was fixed to 200 mW.

*Outdoor Scenario:* The measurement was conducted with one BS and one MT, i.e. we considered an isolated link. The MT is synchronized to the BS. The scenario was a typical urban scenario with a mixture of LOS and NLOS and multipath propagation between buildings. The BS antenna was placed above rooftop at the Heinrich-Hertz-Institut (HHI) at a height of 60 m. One MT was placed in a car which was moved with 5 to 10 km/h on the measurement track, which is depicted in **Fig. 2**.

*Antenna Configuration:* In order to facilitate SMUX in LOS scenarios, cross-polarized antennas

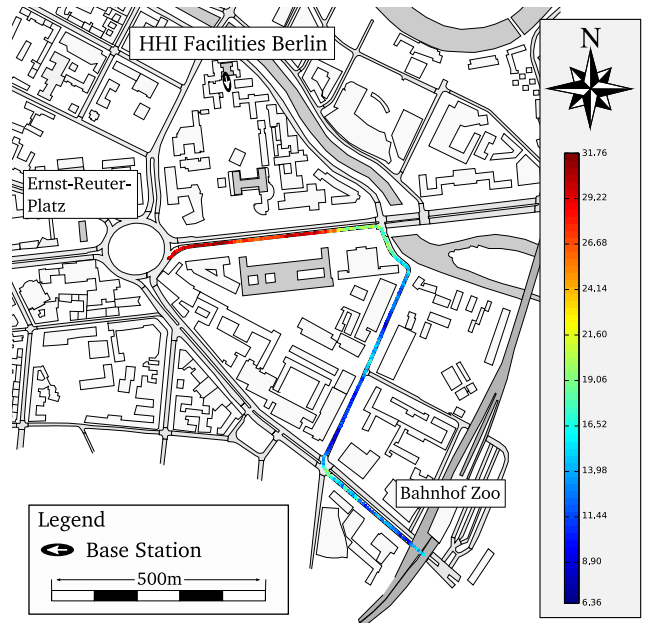


Fig. 2. Outdoor measurement scenario showing HHI facilities on top of the picture and the outdoor test route which covers a BS to MT distance from 200 m to 1150 m

were used at both BS and MT during the measurement campaign. This is also known as polarization multiplexing [20], [21].

The MT is installed inside a measurement van with the antennas mounted 30 cm above rooftop of the car. The two MT antenna polarizations are positioned vertically and horizontally. The route consisted of areas with very low, medium and very high path-loss covering a dynamic range between -90 dBm and -45 dBm at the Rx antennas of the MT. The signal to noise ratio (SNR) averaged over both receive antennas of the MT along the measurement track is depicted in **Fig. 3**.

### IV. FREQUENCY SELECTIVE SCHEDULING

In this paper, we use a heuristic scheduling algorithm, known as the score-based scheduling policy [18]. It tends to assign distinct users to their best RBs, while simultaneously ensuring fairness on a short time scale. In [18] the scheduler was shown to asymptotically achieve proportional fairness [22]; it was extended in [7] to switch adaptively between multi-user diversity and multi-user multiplexing mode.

First each user aggregates the SINRs for all physical layer modes and then ranks his resources by ordering them according to their SINRs in a descending manner. Corresponding scores chosen from a unique set are assigned. To ensure that the rates

from different transmission modes are comparable, the achievable rates for the ss transmission mode are further weighted with a so-called penalty factor  $w$ . The penalty factor for a ss mode is set to  $w = 1/2$ . Within the resource assignment performed at the BS, the transmission mode and the users to be served are selected based on best score per RB. In the mean, this scheduling algorithm results in assigning an equal fraction of resources to the users served by the same BS. Thus each user may realize an equivalent fraction of his total achievable user rate.

## V. RESULTS

Frequency-selective SINR statistics from measurements are shown in **Fig. 4**. In general, the SINRs for the ss mode exceed those in the ms mode. No pre-coding is used in the measurements, i.e. we have implemented the classical PARC on each resource block ( $\mathbf{C} = \mathbf{I}$ ). The SINRs in multi-stream (ms) (multi-stream) mode are lower due to the splitting of power amongst antennas.

**Fig. 4** further shows the quantization of the SINRs based on 1 and 5 bit. A 1-bit quantizer may be seen as a simple threshold decision, where resources capable of realizing a rate of a given magnitude are selected for transmission. It is obvious that a 1-bit feedback quantization penalizes users close to the cell edge having low SINRs. Users at the cell center certainly have SINRs above the threshold and thus will be served.

In the case of 5-bit quantization, low as well as high SINR values are reported with higher granularity. This enables to conveniently support cell edge users and at the same time increases the total achievable rates. By extending the quantization range to higher SINR values as described in section II-A also high-rate user will benefit when more feedback bits are provided.

We use Shannon's formula to come from SINR values to achievable rates  $C = \log_2(1 + \text{SINR})$ . In **Fig. 5**, the overall sector throughput and the 5-percentile of the user throughput, usually representing condition for cell edge users, are shown for measurements (blue) and multi-cell simulations (red). The rates at system level are in general lower compared to the testbed measurement results where no inter-cell interference is present, resulting in reduced the SINRs. Note that the qualitative scaling of the throughput versus the number of feedback bits is similar for both cases.

As expected, the throughput rises monotonically with the number of bits used for the SINR quan-

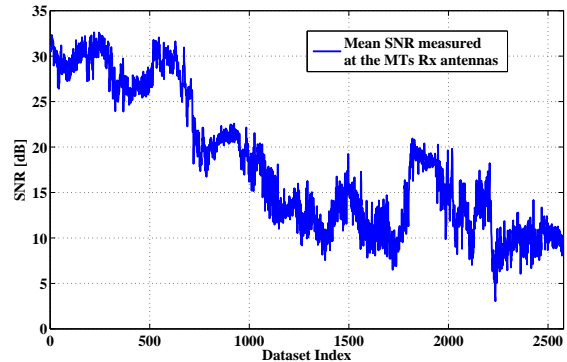


Fig. 3. Mean SNR measured at the receive antennas of the MT along the measurement track, (Fig. 2)

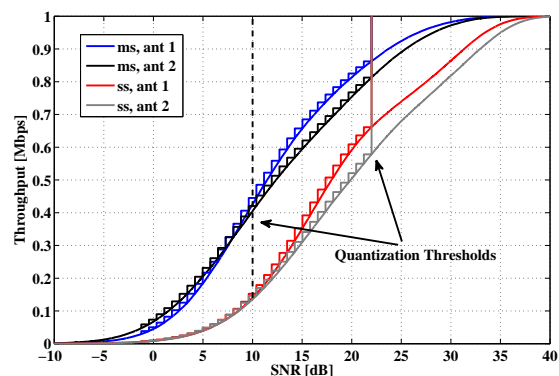


Fig. 4. SINR for single- and multi-stream transmission with and without feedback quantization (1 and 5 bit).

tization. Note that the performance for cell-edge users can be improved by more than one order of magnitude if the number of feedback bits per resource block is increased from 1 to 6 bit. The corresponding improvement for cell-center users is much smaller, but still achieves a factor of 2 over the same range. As already depicted above, service for cell-edge users can be improved significantly.

## VI. CONCLUSIONS

We have considered feedback design for the integration of multi-user MIMO in cellular mobile radio systems. As performance measure we used the throughput based on the quantized SINRs, which is achieved with a score-based scheduling approach. We compared results from system level simulations with measurement data obtained from testbed field trials. Most interestingly both show similar behavior, revealing that the cell-edge users benefit the most from an increased amount of feedback bits. If the feedback rate is fixed, one might use a

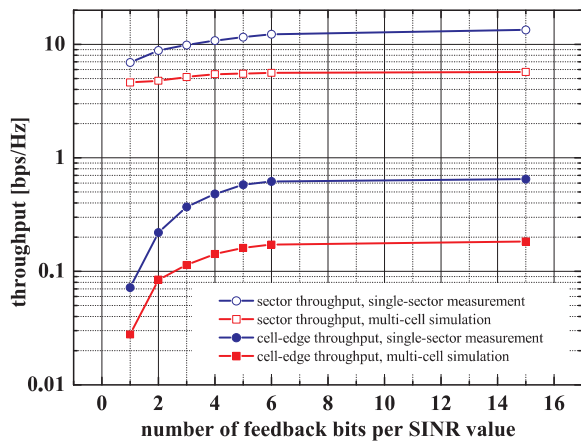


Fig. 5. Median cell throughput and 5-percentile of the user throughput

coarse quantization for terminals having a higher velocity but send their feedback more frequently. For stationary terminals, the update period can be reduced or the SINRs can be quantized with a larger number of bits to achieve a better adaptation to the channel. If users are distinguished according to their average SINR conditions to form user classes, e.g. cell-edge and cell-center users, it might be beneficial to consider class specific quantization ranges for them. Further research should consider efficient source coding techniques to compress the frequency-selective feedback needed for efficient multiuser MIMO scheduling.

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