

# Interference-Aware Scheduling in the Multiuser MIMO-OFDM Downlink

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## ABSTRACT

With the introduction of orthogonal frequency-division multiplexing and multiple antennas in cellular networks, there are new opportunities to adapt the transmission to propagation and interference conditions. In this article we describe a practical approach using space-frequency-selective multiuser MIMO scheduling. Frequency-selective feedback is provided on achievable data rates for preferred single- and multistream transmission modes. The base station selects the best mode while providing instantaneous fairness. We observe that multiuser transmission increases the probability of using multistream transmission. Besides the benefits from optimal combining at the physical layer, there is an additional gain at the MAC layer since the estimation of achievable rates becomes more precise. Altogether, 93 percent of the theoretical throughput can be realized by synchronizing the base stations and providing cell-specific reference signals. We have implemented essential functions of the approach in real time on an experimental 3GPP LTE prototype in 20 MHz bandwidth. Feasibility of the key features is proven in laboratory and field trials.

## INTRODUCTION

Interference is the limiting factor in cellular radio systems. The Global System for Mobile Communications (GSM) typically reduces interference by avoiding the same frequency again in the next cell. In order to increase spectral efficiency, the frequency reuse factor has been reduced down to unity in the Universal Mobile Telecommunications System (UMTS), that is, the same resources are assigned in adjacent cells. The severe intercell interference is whitened by spreading the data over the entire system bandwidth and scrambling them with a cell-specific sequence. In high-speed downlink packet access (HSDPA), terminals provide regular feedback about their mean channel and interference situation using a channel quality indicator (CQI). Depending on this CQI, the entire system bandwidth can be assigned temporarily to the particular terminal that has the best channel. If we consider the terminals in a cell as a virtual antenna array, this scheduling

approach is similar to selection combining and exploits what is called multiuser diversity [1]. Note that the CQI may include information about the interference. Assigning the channel to the user with the best CQI can be regarded as a technique to actively handle the interference.

The downlink of the Third Generation Partnership Project (3GPP) Long-Term Evolution (LTE) is based on orthogonal frequency-division multiple access (OFDMA). It has the potential for enhanced interference reduction compared to previous systems based on code-division multiple access (CDMA). At least for stationary users there is no more intracell interference, since orthogonal frequency-division multiplexing (OFDM) waveforms remain orthogonal after passing through a multipath channel. As a novelty, we can exploit the multipath nature of signal and interference channels in the scheduling process. Simply speaking, one assigns those parts of the spectrum to a user where simultaneously the desired signal is strong and the interference weak. In addition to the time-domain scheduling already used in HSDPA, groups of subcarriers can be assigned to users according to the frequency-selective signal and interference conditions.

Multiple-input multiple-output (MIMO) techniques use multiple antennas at both the base station (BS) and the terminal. MIMO is expected to contribute substantially to the enhanced capacity of LTE. Note that OFDM simplifies the signal processing for MIMO. Simple MIMO algorithms for flat fading channels are sufficient for channel equalization [2]. To maximize the benefits of the new air interface, our objective is to minimize the effects of interference by means of joint radio resource management for multiple users in a cell exploiting the new degrees of freedom in the frequency and space domains. Our approach is similar to a spectral decomposition of the colored interference and adapting the transmission accordingly.

Let us first define essential requirements for the downlink MIMO medium access control (MAC) layer. Resource assignment needs fairness in a cellular network in order to guarantee the best throughput for all users. With opportunistic approaches as in [1] a user at the cell edge is never served. A common implementation

is proportional fairness: In the mean, the user is assigned a constant fraction of the rate he could realize if he was alone in the cell. To realize low packet delays, which are a general requirement of LTE, the possibilities of resource assignment are rather limited in the time domain. For traffic with high priority a free resource shall always be available for a user having poor channel conditions. For critical real-time multimedia services such as videoconferencing, instantaneous fairness may be desirable. The score-based scheduler provides good heuristics to realize these objectives [3].

Feedback reduction is a second requirement for cellular mobile radio systems. A terminal has low power (e.g., 200 mW) and is expected to bridge distances of several kilometers at the cell edge. This is reached by reducing the bandwidth assigned in the uplink and increasing the spectral power density accordingly when moving from cell center to cell edge. Last but not least, the mobile radio channel changes rapidly, and feedback is needed at high repetition rates. Each feedback bit costs battery power and spectral resources; thus, limited feedback is paramount. Here we consider feedback on the order of several tens of kilobits per second, which may be feasible even at the cell edge. With such a low rate it is possible to feed back a coarse characterization of the MIMO channel as a function of frequency based on a CQI for several spatial transmission modes and certain groups of sub-carriers.

Efficient spatial adaptation is a third requirement. A MIMO system can in principle select the operation point in the diversity gain vs. multiplexing gain plane [4] by using a particular transmission mode according to the channel conditions. Such MIMO mode switching is helpful to achieve the best possible transmission rate in a mobile scenario. Diversity transmission is favored in low-rank channels having, say, a free line of sight (LOS) to the BS, while multiplexing is preferred when the rank is full and the effective signal-to-interference-and-noise ratio (SINR) is at a sufficient level. Sometimes higher throughput may be realized if not all the streams are used for spatial multiplexing. Selection can be based on the achievable rates for various spatial transmission modes calculated at the receiver side. The preferred mode and corresponding rates are fed back to the BS where the radio link is optimized [5]. Refer to [6] for an initial proposal of frequency-selective MIMO mode switching. Single-cell performance with two-user support is investigated in [7], and fair scheduling for multiple users in [8]. Multicell performance is analyzed in [9]. Physical and MAC layer implementation and early field trials are reported in [10].

Two more requirements not currently met by LTE Release 8 (R8) are needed. Knowledge about the interference could be obtained from the covariance matrix of the received signals. However, such estimation is not precise enough. The temporal variation of the covariance can hardly be tracked in a mobile scenario, and the potential gains are ruined [11]. As a way out, we propose to synchronize the BSs (e.g., by GPS or over the network using the IEEE 1588v2 stan-

dard [12]) and provide cell-specific reference signals. At each terminal, the channels to the strongest BSs are estimated [13]. The covariance is then calculated from these multicell channel estimates.

The article is organized as follows. We start with the spatial mode switching concept and describe our instantaneously fair scheduling algorithm. We highlight two recent observations: First, the more statistically independent degrees of freedom we offer to assign spatially multiplexed streams (e.g., frequency-selective feedback, multiple users, multiple beams), the higher the probability of using the multistream mode. Next we show that if the channel to the interfering cells is known in addition to the serving one, the estimation error for the achievable rate on the MAC layer is significantly lower. The system can be loaded less conservatively, and this transforms into an overall throughput gain. For these reasons, the spectral efficiency is significantly enhanced. The MIMO capacity scaling for point-to-point links, proportional to the minimum of the numbers of transmit and receive antennas, can also be approximated in this way in the multicell scenario. Real-time implementation and laboratory as well as field trials are described to show the feasibility of our approach.

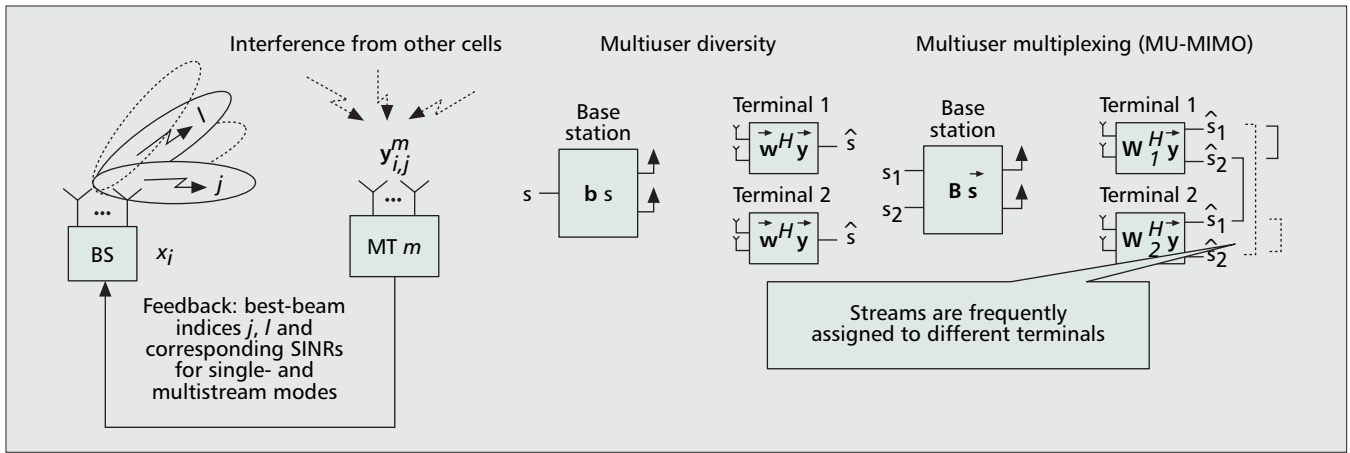
## THE SPATIAL MODE SWITCHING CONCEPT

The concept is based on a fixed grid of beams provided by the BS consisting of a number of beamforming vectors  $\mathbf{b}$  given in a predefined codebook (Fig. 1, left). The physical layer supports two principal transmission modes: single-stream (ss) mode for spatial diversity where a single user is served exclusively on one beam, and multistream (ms) mode for spatial multiplexing where independent data streams are transmitted in parallel on multiple beams. For each supported mode, a terminal determines the achievable rates per beam and conveys this information to the BS. The setting of the modes can be selected individually for each available frequency subband, also referred to as a resource block (RB).

In particular, for the ss mode, the effective post-equalization SINR is determined for each beam  $\mathbf{b}$  after optimum combining at the terminal. From the SINR, the achievable rate per beam is estimated. The highest beam rate together with the corresponding beam index is then fed back to the BS.

For the ms mode, we extend the common optimum combining (OC) approach to separate spatially multiplexed streams at the terminal side. Optimum combining provides the best filter weights for isolating a desired signal out of the co-channel interference from all other signals like intra- and intercell interference. At the BS, we allow  $Q$  beams to be simultaneously active. Active beams are taken from the columns of the unitary matrix  $\mathbf{B}$ , also called a beam set in the following. The codebook may contain multiple such sets. The rate supported on each of the  $Q$  spatially multiplexed streams is estimated. The per-stream rates for the particular matrix  $\mathbf{B}$  from

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■ **Figure 1.** Left: transmission concept based on a fixed grid of beams. The terminal calculates the achievable rates in single- and multi-stream modes for preferred beams and feeds those back to the base station. Right: mode switching options; option 1 — classical multiuser diversity; option 2 — SU-MIMO, both streams are assigned to one terminal; option 3 — MU-MIMO, the streams are assigned to different terminals.

the codebook achieving the highest per-stream rate and the codebook index corresponding to this matrix are fed back to the BS.

The BS may select one out of three options for spatial transmission (Fig. 1, right). In ss mode the terminal providing the best rate is selected to achieve multiuser diversity. For the ms mode, there are two options. Streams may be assigned to the same terminal as in classical single-user spatial multiplexing (SU-MIMO). Alternatively, the available beams can be assigned to different users (multiuser spatial multiplexing [MU-MIMO]). Note that the streams are separated at the terminal side. The striking advantage of this proposal is that it enables MU-MIMO access at a very low feedback rate. MU-MIMO can be supported without having coherent information on the downlink channel at the BS: only the achievable rates and the preferred codebook indices must be reported for ss and ms mode.

## INSTANTANEOUS FAIRNESS

A transmission time interval (TTI) in LTE lasts 1 ms and consists of two slots. At 18 MHz bandwidth 100 RBs are accommodated, each having a bandwidth of 180 kHz. The RBs can be individually assigned to users. The objective of resource allocation is to assign each user its best resources in a frequency-selective manner, whereby the decision on the spatial mode should be made under the premise of achieving high throughput while targeting proportional fairness among users. In this section we describe our frequency-selective scheduling algorithm. It is based on a two-step approach.

In step 1 the terminal evaluates for each RB the achievable rates for all spatial transmission modes and selects the best codebook entries accordingly. The achievable rates for each mode are quantized and fed back as a frequency-selective CQI together with the preferred spatial mode index (PMI). This PMI contains the index of the best beam in ss mode and the index of the best beam set, and which subset of the beams is used in ms mode.

CQI as well as PMI are RB-specific information. At the BS, we collect the CQI and PMI vs. frequency vectors from all terminals. For each terminal, the CQIs for all RBs are put in separate lists for each transmission mode. These lists form the basis for extending the original score-based scheduling approach [3], which assigns each transmission resource a score representing a quality rank. The key to enable a direct comparison of ss and ms rates is the introduction of a so-called benefit factor for the rates in the multiplexing mode. As we aim for high spectral efficiency, mode selection should favor the ms mode if the user rate can be expected to be larger than the rate expected in ss mode.

If a user decides globally on ms mode, the total available spatial streams compared to ss mode are multiplied by the factor  $Q$ . Accordingly, the terminal will be assigned  $Q$  times the resources it would get if it globally selected the ss mode. The ss mode thus should be favored only if

$$R_{ss} > Q \cdot \max_i R_{ms,i},$$

where  $R_{ss}$  and  $R_{ms,i}$  are the single- and multi-stream rates reported on stream  $i = 1 \dots Q$ . To include this as a benefit, the rate list for the ms modes is weighted by the factor  $Q$  and concatenated with the rate list containing the ss rates. Using the concatenated list, joint sorting is performed. By this procedure we yield a ranking not only of the different RBs, but implicitly also of the different supported transmission modes. This ranking (i.e., the order of entries in the sorted list) is represented by the score.

Step 2 addresses resource scheduling, which is performed separately for each RB. All user scores for that RB are first partitioned according to the transmission mode they refer, ss or ms. User selection is at first carried out for each transmission mode separately, and then a final decision on the mode is made. In ss mode the user is selected providing the minimum score for that mode. In ms mode users choosing the same beam set  $\mathbf{B}$  are candidates for MU-MIMO and are thus put into one group. In this group

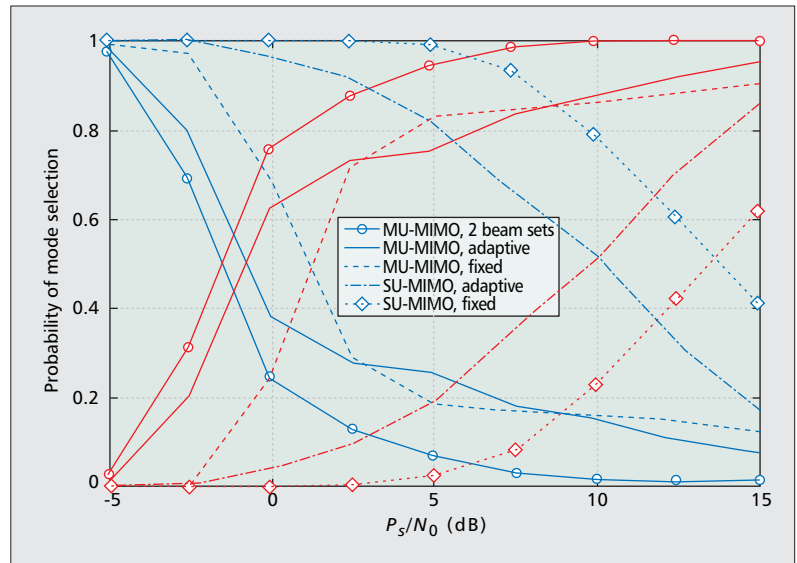
each of the  $Q$  available beams is assigned to the user providing the minimum score for that beam. Obviously, this user selection also includes classical SU-MIMO, as all streams may be assigned to one user. After user selection has been carried out for each of the available beam sets, we pick the set containing the user with the minimum score. Finally, we compare the minimum of the scores provided by the selected ms user(s) with the score of the user favored in ss mode and select the mode yielding the total minimum.

## SINGLE-CELL RESULTS

As already mentioned, an in-depth performance analysis of the spatial mode switching concept is reported in [7, 8]. Here we highlight a more recent observation revealing why the spectral efficiency of this scheme is substantially higher than SU-MIMO transmission as suggested in LTE R8. In our single-cell analysis we have grouped 10 users *on a ring* around the BS; that is, the average signal-to-noise ratio (SNR) is identical for all users. Normalized channels are obtained from the 3GPP SCME channel model in the urban macro scenario. Terminals and the BS are each equipped with two antennas. The model assumes a uniform linear array of co-polarized antennas where antenna spacing at the BS is four wavelengths, yielding a minor correlation between antenna signals. User channels are modeled independently. A bandwidth of 18 MHz is used, accommodating 100 RBs of 12 subcarriers width each. We have used the unitary beam sets C1 and C2 defined in [14]. Potential ss transmission selects a single beam out of the available beam sets and allocates the entire power to that beam. In ms mode the transmit power is distributed equally over the  $Q$  active beams. Potential ms modes are either MU-MIMO, where one stream is assigned to a first user and the second stream to a second user, or SU-MIMO, where both streams are assigned to the same user.

In Fig. 2 the probability of ss and ms transmission is compared as a function of the SNR for different scheduler constraints. Note that better spectrum utilization and higher throughput is typically achieved if the probability of ms mode is increased. In the first two curves (*SU fixed* and *SU adaptive*), an RB is always exclusively assigned to one user, which is still allowed to choose diversity or multiplexing as transmission mode (SU-MIMO). For the fixed configuration, transmission mode as well as the beam set is fixed per user. Selection of the fixed mode and beam set is based on the highest sum rate over the entire frequency band. Hence, a user reports RB-specific CQI and global PMI. For the adaptive configuration, the user is allowed to choose the transmission mode and beam individually per RB. By comparing the curves of SU fixed and SU adaptive in Fig. 2, it is observed that the crossing point between the ss and ms probability moves by 3 dB to lower SNR by allowing frequency-selective mode selection.

A striking shift of the crossing point is observed if MU-MIMO is enabled. For the fixed configuration, the crossing point is remarkably



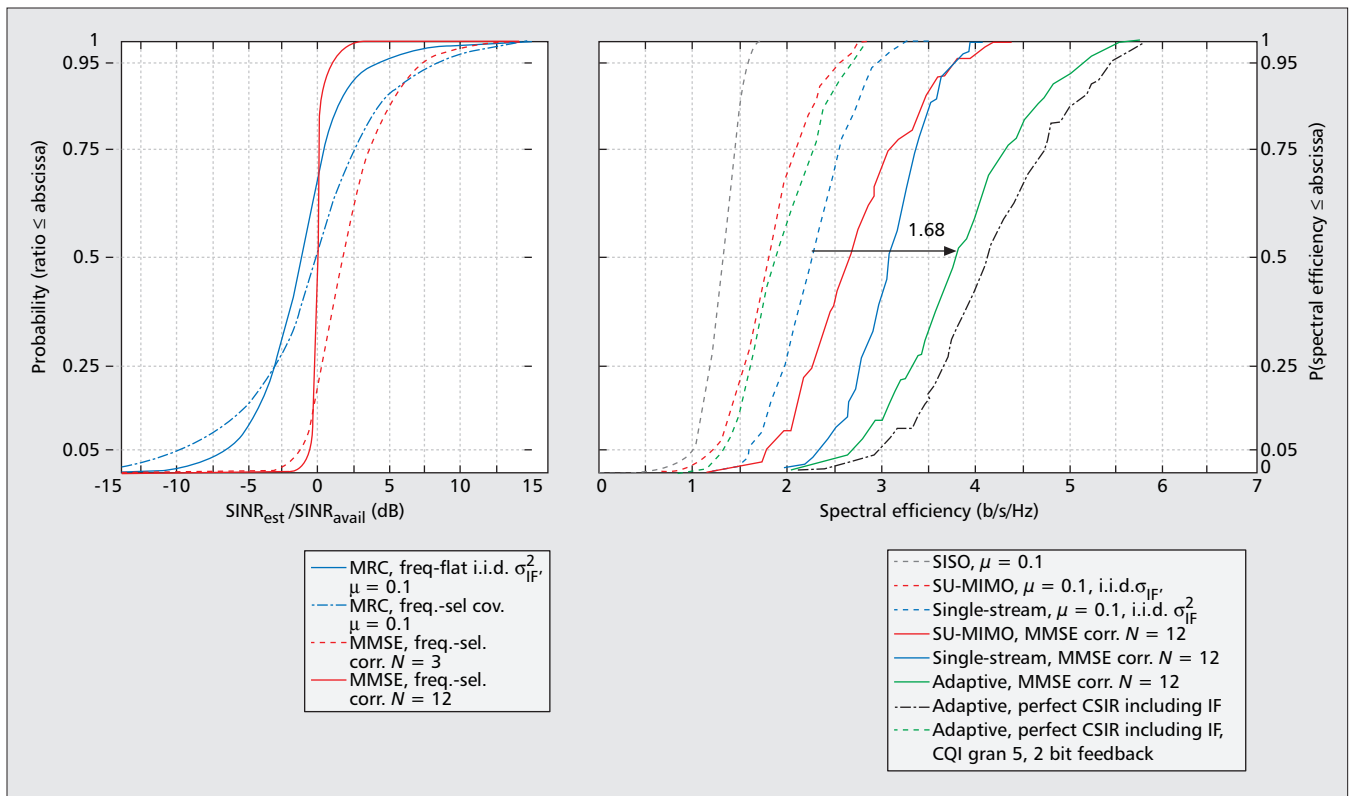
■ **Figure 2.** Probability of mode selection for ms mode (red) and ss mode (blue) vs. SNR. In the legend SU means that RBs are always exclusively assigned to a single user, while MU means that multiple users can share an RB. The word fixed means that the spatial mode of a user is set constant for the whole frequency band, while adaptive means that the spatial mode of a user may change per RB.

shifted from 13 dB down to 2 dB with 10 users. For the adaptive configuration, the crossing points of the MU curves shifts below 0 dB. Note that the curves considered so far have used only beam set C1. If two beam sets are enabled (left-most curves in Fig. 2), the crossing point shifts to -2 dB. Throughput gains resulting from frequency-selective MU-MIMO with 10 users in 20 MHz in a single cell are between 24 and 30 percent at low and high SNR, respectively (not shown).

## MULTICELL RESULTS AND THE IMPACT OF CHANNEL ESTIMATION

By introducing this scheduling approach, the likelihood of the ms mode is remarkably enhanced in the particular range of interest for cellular systems with full frequency reuse. One may expect, therefore, that users are preferably served in multiplexing rather than in diversity mode even at the cell edge. This would imply that cell edge users could be served in a spectrally more efficient way.

Let us first mention a difficulty introduced by the above mentioned option to select variable beam sets, which has a positive effect in a single cell. In a multicell environment fast beam set selection would destroy the causality in the scheduling process. If the set chosen in an adjacent cell changes rapidly, the interference is no longer predictable in the cell of interest, and rescheduling should take place. As a consequence, we abstain from using this option on a short timescale in the multicell case in favor of making the interference more predictable. Beam set selection may be used on a longer timescale (e.g., for optimizing the cell geometry). Furthermore, for calculating the SINR we have assumed



■ **Figure 3.** Left: estimation error of the estimated  $\text{SINR}_{\text{est}}$  in ss mode compared to the available  $\text{SINR}_{\text{avail}}$ . Right: throughput of various transmission schemes including the estimation errors.  $\mu$  is the mean square error of the channel.

that surrounding cells use the ms mode permanently on all RBs. Taking mode switching in adjacent cells into account would not substantially change our results since ms transmission is favored, as shown above.

In this section we describe a second contribution to the enhanced throughput being obvious only in the multicell scenario. Note that besides the channel of the desired signal, the interference from other cells is also time and frequency selective. LTE R8 has adopted the traditional interference whitening approach. Based on cell-specific scrambling sequences applied to pilots along the frequency axis, we can estimate the wideband averaged SINR by frequency domain correlation with the sequences of the strongest cells. However, this averaging in the frequency domain has a negative impact on the achievable throughput. Both the desired signal and interference plus noise term remain random numbers on a given RB, and their ratio determines the achievable rate on that RB, which is not at all a constant number. Since the interference is not precisely known for each RB, however, we have to apply empiric safety factors reducing the mean SINR and taking into account that there are in fact variations in the frequency domain. Accordingly, a conservative rate is assigned to users independent of frequency.

Frequency-selective SINR estimation is a promising way out. BS synchronization [12] and the introduction of pilots allowing an estimation of the frequency-selective channel for adjacent BSs [13] enable both better suppression of the interference at the physical layer and more pre-

cise SINR estimation as well. In the following we also include the effects of channel estimation errors due to multicell interference.

As a reference, maximum ratio combining (MRC) is used, where the interference is estimated in different ways. First, the interference is assumed white over both antennas and frequency. This case is similar to LTE R8. Second, we obtain the colored spatial interference by estimating the covariance matrix of the received signal vectors. These are the techniques that can be realized using asynchronous transmission.

In contrast, we consider a synchronized network and a more sophisticated linear receiver such as OC having coherent knowledge about the co-channel interference. OC is also referred to as the minimum mean square error (MMSE) receiver. The interference covariance is calculated here from the multicell channel estimates rather than measured from the data signals as in the asynchronous case. In [13] we have proposed virtual pilot sequences identifying the cells by which the conventional pilots are scrambled in the time domain. The estimator uses a sliding correlation window over several slots. Increasing the correlation window yields more precise identification of interferers in general but limits the mobility. A correlation length of one slot refers to a window size of  $N = 3$  chips in the sequence (i.e., the sector groups can already be distinguished). By extending the sequence over four slots ( $N = 12$ ) we can distinguish groups of four adjacent sites. The following results include the residual estimation errors of the multicell channel if the cells use the virtual pilot sequence assignment in [13].

Figure 3 (left) illustrates a first result using the estimation error in ss mode. We compare the ratio of the estimated SINR to the theoretically achievable value by employing either MRC in an asynchronous network or MMSE in a synchronized one. In the asynchronous network, we assume that the SINR is estimated in wideband mode, as in 3GPP LTE R8. In the synchronous network the SINR is obtained in a frequency-selective manner after channel estimation based on virtual pilots as described in [13].

For MRC with frequency-flat knowledge of the interference power  $\sigma_{\text{IF}}^2$ , the estimation suffers in two ways. First, there is a median shift of  $-1$  dB in Fig. 3 (left), meaning that the estimated SINR is systematically too low and more data could be transmitted than expected. Second, the estimation error has a considerable variance. Only for the RBs where the estimation error is 0 dB are the user rates assigned precisely. For other RBs, the achievable rates are randomly over- and underestimated, and we have to apply a safety factor  $S < 1$  to the estimated SINR with the intention that the assigned rate is feasible (e.g., in 90 percent of cases). The complementary 10 percent of the bits in a transport block (TB) are mapped onto bad RBs where the channel is overloaded and probably cannot be recovered correctly. Powerful turbo codes with interleaving across the resources assigned to a user and hybrid automatic repeat request (HARQ) can repair such errors. Nevertheless, the safety factor  $S$  remains, and it implies a penalty for the overall system throughput. For MRC, we can estimate  $S = -2.8$  dB from Fig. 3, and with the shifted median of  $-1$  dB there is an overall penalty of roughly 3.8 dB at the MAC layer compared to the theoretically achievable SINR.

Direct estimation of the covariance leads to an unbiased SINR estimation (see the dashed blue line in Fig. 3, left). But the  $S$ -factor is high due to the huge variance of the estimation error. It is caused by the interference-limited channel estimation in the serving cell and the short averaging interval of two slots assumed for the covariance. The overall penalty is 6.3 dB. Due to this penalty, it makes little sense to combine frequency-selective covariance estimation with either MRC or MMSE. Consequently, MRC with white interference assumption<sup>1</sup> fits well with asynchronous transmission.

But we can do better if the BSs are synchronized and the interference is estimated. This has been done for MMSE. With a correlation window of 1 slot ( $N = 3$ ), interference from adjacent sites cannot be separated. The SINR is systematically overestimated (Fig. 3, left). Already with a correlation window of four slots ( $N = 12$ ) more interferers can be identified, and the SINR is computed more precisely. Then we get  $S = -0.9$  dB and the bias becomes negligible.

Based on multicell channel estimates, the performance can be improved additionally at the physical layer using the MMSE receiver. In Fig. 3 (right) we have plotted the achievable rates in the multicell system including channel estimation errors.<sup>2</sup> As a lower bound, we have given the performance in the SISO case where the minor effect of estimation errors is included as well. If the spatial interference is assumed white,

the performance of single-user ms transmission gets worse than ss transmission with MRC. The reason is that the estimation error leads to inter-stream interference in the ms case, which is not present with ss transmission. Although the MMSE receiver can exploit the interference knowledge, SU-MIMO transmission still suffers substantially from estimation errors compared to the ss case. Only if the fully adaptive MAC is used, where the streams can be assigned to different users, is there a significant throughput gain. By including the MU-MIMO gain, the ms mode becomes really efficient in the multicell scenario. The gap to the adaptive system with perfect channel and interference knowledge is only 7 percent, indicating that the proposed scheme is very robust against channel estimation errors.

An essential condition for realizing the potential gains is also illustrated in Fig. 3 (right). Targeting simple feedback compression, one might want to combine CQI values (e.g., for five consecutive RBs) and reduce the feedback quantization to 2 b/RB group. However, such a simple compression would ruin the potential gains. The CQI information must be available at the BS RB-wise and with 5-bit granularity [16], which needs smarter compression. A promising way is to exploit the channel correlations in time and frequency domains (i.e., to apply efficient source coding techniques).

Let us finally compare asynchronous and synchronous transmission. In the asynchronous case one would prefer ss transmission because of the detrimental effects of estimation errors in the ms case. In the synchronized case with multicell channel estimation, the average throughput gain is about 68 percent of that in asynchronous SU-MIMO transmission according to the results in Fig. 3 (right). Despite the estimation errors, we can realize 93 percent of the theoretically predicted performance. As shown in [9] where channel estimation and feedback are assumed ideal, the throughput also scales linearly with the number of antennas in the interference-limited scenario.

## REAL-TIME IMPLEMENTATION

Essential features of the concept have been implemented in a real-time prototype with the aim to prove the feasibility of frequency-selective MU-MIMO scheduling.<sup>3</sup> The system is operated in frequency-division duplex mode in the 2.6 GHz band identified for future LTE deployment in Europe. Downlink and uplink are operated at 2.68 GHz and 2.53 GHz, respectively. The bandwidth can be scaled from 1.5 to 20 MHz. BS and test terminals called user equipment (UE) are each equipped with two antennas. Total transmitter powers are +43 dBm at the BS and +23 dBm at the UE. The OFDM system uses 2,048 subcarriers with 4.7  $\mu$ s cyclic prefix. The 10 ms radio frame contains 20 slots of 0.5 ms duration each.

In each downlink slot seven OFDM symbols are transmitted. Representing the ss mode, antenna selection has been implemented together with MRC at the receiver where the active transmit antenna can be selected for each RB.

*The CQI information must be available at the BS RB-wise and with 5 bits granularity [16], which needs smarter compression. A promising way is to exploit the channel correlations in time and frequency domains, i.e., to apply efficient source coding techniques.*

<sup>1</sup> That is, averaged over both frequency and antennas.

<sup>2</sup> Overhead has been ignored here since it depends on the particular system design.

<sup>3</sup> Development has been started in the early phase of the LTE study item. A few technical details have become obsolete, and proprietary simplifications of the standard are included in this early implementation. There is minor impact on the performance.



**Figure 4.** Testbed hardware. Left: base station hardware for one sector. Center: antenna setup on top of the TUB main building. Right: test terminals in the measurement van.

For the ms mode two data streams are transmitted in parallel using polarization multiplexing, and a linear MIMO MMSE filter is implemented at the terminal side. The transmitter and receiver can be switched between ss and ms mode in each RB and each scheduling interval by an adaptive data mapping unit at the BS [10], while a vector and a matrix are applied as filter weights at the receiver, respectively, according to control information provided with the data.

In the uplink, contiguous subcarrier blocks are assigned to a user. Data are passed through a discrete Fourier transform (DFT) prior to mapping them onto the frequency domain. Our test terminal radio frontends have two transmit antenna ports. Cyclic delay diversity (CDD) is used in combination with MRC at the receiver to overcome power limitations. The terminal is remotely synchronized to the BS (i.e., the frequency offset is precompensated in the uplink). Timing advance is measured using a terminal-specific sequence and steered dynamically over the downlink control channel. For more details of the physical layer implementation refer to [15].

At the MAC layer, and in the 2.5, 5, 10, and 20 MHz modes the frequency-time grid is subdivided into 6, 12, 24, and 48 RBs, respectively. A RB consists of 25 subcarriers and 7 OFDM symbols each. 144 complex data symbols are mapped into each RB; other resources are used as pilots. In 20 MHz mode, up to 48 RBs can be assigned to an individual user on each transmit antenna. All RBs assigned to a particular user in a slot form a variable-length TB. Going beyond LTE R8 we have enabled a finer granularity of adaptation to the frequency-selective channel by also allowing adaptive modulation and adaptive MIMO mode selection within a TB: each RB may be loaded with different modulation formats from quaternary phase shift keying (QPSK), 16-quadrature amplitude modulation (QAM), and 64-QAM, and operated in either diversity or multiplexing mode.

Coding is performed over all RBs assigned to a user in a TB. Supported code rates are 1/2 and 3/4; the minimum word length is 432 bits, corresponding to the smallest TB size. Convolutional

coding was chosen to reduce the hardware effort. It is critical for the performance to interleave all bits in one TB and realize frequency diversity in this way even if adaptive modulation is used within the TB.<sup>4</sup> At higher mobility the delays in the feedback and control loop become long compared to the coherence time, and resource assignment might be outdated. Note that the interleaved adaptive modulation enables both significant throughput gains at low mobility and diversity gains at high mobility. For further mobility support, the SINR threshold of QPSK (denoted on-level) can be modified depending on the bit or packet error rates. The thresholds for other modulation formats are coupled to this level. If the error rate increases (e.g., because of higher velocity), the on-level is increased dynamically. The overall rate is then reduced, and the link is stabilized at a lower data rate.

We have implemented proprietary feedback and control channels. For both ss and ms modes the achievable rates on both antenna ports are quantized by 8 b/3 RBs. In 20 MHz bandwidth this gives 128 bits of frequency-selective feedback information transmitted each 10 ms (i.e., 12.8 kb/s). The information is mapped on a short control TB in a particular slot and transmitted using binary PSK (BPSK) modulation with rate 1/2 over the shared uplink channel. The downlink control channel is transmitted in a dedicated slot containing the complete downlink and uplink resource map for an entire radio frame. A proprietary compression format called Tetris is used. In principle, the corners of the resource areas assigned to a user in the time-frequency map are transmitted, not the detailed information for each RB. Control information is transmitted with QPSK rate 1/2 in single-stream mode using CDD at the transmitter and MRC at the receiver.

The hardware is shown in Fig. 4. BS equipment for one sector is placed in an outdoor housing (Fig. 4, left). Radio front-ends include two transmit-receive chains and the dual amplifier and combiner unit containing the duplex filters. The RF unit is coupled to the LTE signal processing unit (LSU) via common public radio interface (CPRI) operating at 1.2 Gb/s. The

<sup>4</sup> For final resource mapping, rate matching of allocated resources and modulation and coding schemes is implemented.

LSU consists of two motherboards with two Virtex2Pro-100 FPGAs each, four and one TI 6713 DSP for the equalization and scheduling algorithms in the receiver and transmitter branches, respectively, and two Virtex4 FPGAs realizing the interface to 1 Gb/s Ethernet as well as CPRI. Sector antennas with +18 dBi gain, 60° horizontal, and 5° vertical beam-widths and electrical down-tilt are used.

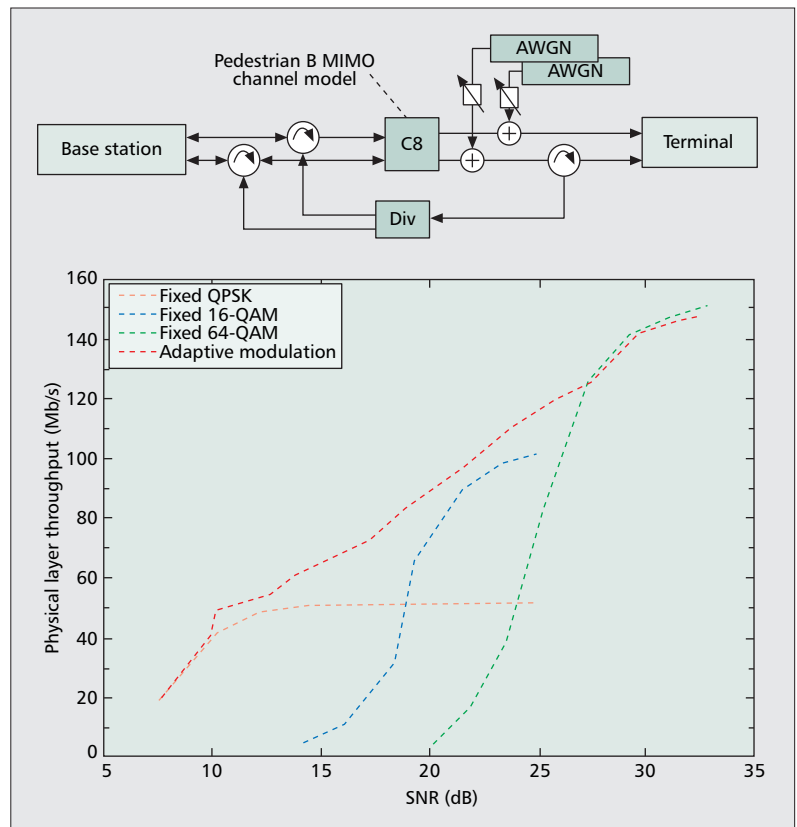
The test mobile is shown in Fig. 4 (right). It is fixed in a standard 19 in box with three height units. The same reconfigurable signal processing platform is used as for the BS. Differences are in the smaller RF front-ends and the Li-ion battery pack for 3 h mobile operation. Note that sophisticated coarse and fine synchronization techniques are used so that the test mobile can be unplugged and used for real-time communications in the field.

## LABORATORY AND FIELD TRIALS

We have tested the implementation in the laboratory using a wideband channel emulator. The setup is sketched on top of Fig. 5. Two transmit antenna signals are fed into the emulator, where the Pedestrian B channel model is used having maximal delays as large as 3.7  $\mu$ s (i.e., 3/4 of the cyclic prefix). Fine timing is critical in this channel. Physical noise is added after the emulator, and the signal is fed into the terminal. The SNR is set using a variable attenuator and checked carefully using a spectrum analyzer. Uplink and downlink paths are separated using circulators. At the terminal side, the physical layer goodput is measured. It is given as the scheduled rate times the rate of correctly received packets. Results are plotted in Fig. 5, bottom. With fixed modulation, we measure the typical blurred step-like throughput curves for QPSK, 16-QAM, and 64-QAM, all with rate 1/2. The curves may be steeper when turbo coding is used instead of our convolutional code, and the onset appears at higher SNR. Nonetheless, the performance can be regarded as typical for MIMO in LTE over this channel, and it has been checked thoroughly in the LTE/SAE Trial Initiative (LSTI).

Adaptive transmission has been measured as well. The on-level has been set so that the packet loss rate is below 10 percent. With such a greedy threshold, the measured packet loss varies between 0.2 percent at highest and 9.8 percent at lowest SNR, respectively. The throughput curve touches the fixed mode curves approximately at the points where the targeted packet error rate in adaptive mode is also realized with fixed modulation. The main advantage of adaptive modulation is smoother adaptation to the channel conditions; thus, higher throughput can be achieved in practice. The measured multiuser gain with two users over independent Pedestrian B channels is 40 percent at 5 dB SNR and reduces to roughly 10 percent for SNR > 15 dB. The round-trip delay has been measured as mean (maximum) ping time of 6.5 (7) ms without traffic, 7.3 (11) ms with 64-QAM and 25 Mb/s UDP downlink traffic, and 7.5 (22) ms with QPSK and 7 Mb/s load.

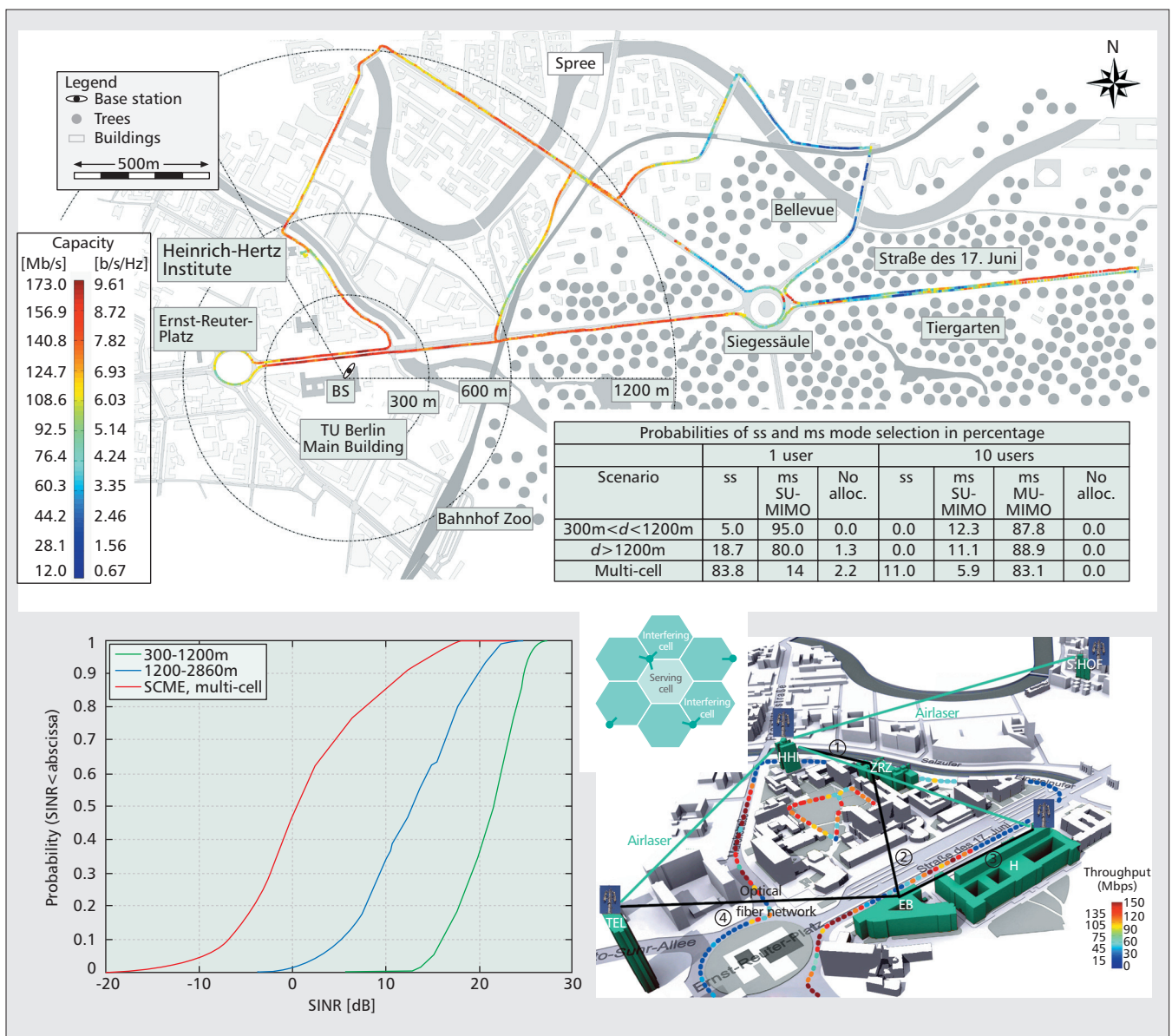
In order to investigate the performance of the adaptive multiuser MIMO MAC under real



■ Figure 5. Top: setup for laboratory measurements. Bottom: measured throughput using fixed and adaptive modulation.

propagation conditions, we conducted outdoor field trials in the city of Berlin. A single-cell scenario is considered. The BS is placed on top of the main building of the Technische Universität Berlin (TUB, Fig. 4, center) at a height of 45 m above the ground and about 10 m above the average rooftop level to realize a typical urban macrocell scenario. The main azimuth lobe of the sector is directed toward 30° measured from north over east, and the down-tilt angle is set to 2°. The BS is part of a test network deployed recently in cooperation with Deutsche Telekom (Fig. 6, bottom right). The setup emulates an elementary interference scenario with four sites, where the site at HHI serves as the sector of interest, and the six surrounding sectors are realized as shown in the inset. Sites are interconnected by 1 Gb/s free-space optical links; in addition, the three sites at HHI, TUB, and T-Labs are linked by optical fibers.

The terminal is installed in a measurement van. Omnidirectional antennas are arranged in a cross-polarized setup on the rooftop. The driving route in the city center of Berlin covers low and high path loss with a large dynamic range from -39 to -92 dBm of received power, respectively. The route goes through areas with dense buildings and the large park area of Tiergarten with dense vegetation. In Fig. 6 (top), the achievable throughput for a single user is shown on the map. Data are obtained by recording the pilots at the terminal side. SINR calculation and scheduling has been done offline.<sup>4</sup> At the small down-tilt angle, distances covered at 2.6 GHz



**Figure 6.** Top: achievable data rate with one user in a single sector with 20 MHz bandwidth. Bottom left: cumulative distributions of the measured SNR in two distance ranges and the SINR in a simulated multicell scenario. Bottom right: multisite test network in Berlin.

range from less than 1 km in typical urban areas with dense buildings up to 5 km when the LOS is free.

In order to illustrate the potential of the proposed multiuser MIMO approach, we consider the selection probabilities for the ss and ms modes in two different distance regions, both valid for realistic cellular deployments. The terminal positions have been sorted according to their distance, between 300 and 1200 m and more than 1200 m away from the BS, respectively. For comparison we include results obtained from system-level simulations, where multicell interference has been taken into account.

In Fig. 6 (bottom left) the distributions of the measured SNR for the two distance groups are compared to the statistics of the SINR in the multicell scenario for individual RBs. Our measurements realize situations typical for users in good and average channel conditions in a multicell scenario. We have placed in each scenario

either a single user or 10 users at a constant distance from each other travelling jointly along the track. The single-user rate as a function of position is shown in Fig. 6 (top). Note that there are only a few blank pixels along the track where the link is lost. All other positions are included in the statistics.

The mode selection probabilities are given in the table embedded in Fig. 6. With only one user at large distances of  $d > 1.200$  m, 18.7 percent of RBs are assigned in ss mode, while for 80 percent ms mode is used. Compared to the relations illustrated in Fig. 2, this is surprising at first glance, since in 60 percent of the locations the SNR is lower than 15 dB here. However, the high ms probability even at lower SNR may be attributed to the cross-polarized antennas used in our field trials. In fact, they help the terminals realize a higher rank of the MIMO channel compared to the co-polarized antennas used in our simulations.

<sup>4</sup> Such offline processing is more realistic to illustrate the potential of the technique. The measured real-time throughputs are smaller due to the simplified feedback compression, as indicated similarly in Fig. 3, right.

For 10 users at  $d > 1200$  m, the probability of ss transmission is reduced to zero. SU-MIMO mode is only selected in 11 percent of cases, while MU-MIMO mode is used for 89 percent of the RBs. This remarkable preference for resource sharing can be observed in the multicell scenario as well. With a single user, the ss mode is clearly favored by about 84 percent of the RBs, due to the low SINR in the interference-limited scenario. Only 14 percent of the RBs are assigned in ms mode, as only those terminals with excellent channel conditions can benefit from spatial multiplexing. The situation is now completely reversed if MU-MIMO is enabled. With 10 users, the ss probability collapses down to 11 percent while as much as 89 percent of the RBs are assigned in ms mode: spatial multiplexing becomes suddenly dominant if resource sharing is enabled in the multicell scenario.

## CONCLUSIONS

We have outlined the potential of using frequency-selective multiuser MIMO scheduling in a further evolved cellular network in which BSs are synchronized and terminals are enabled to estimate not only their own channel but also the channels of interference signals from other cells. We observe that the more statistically independent degrees of freedom the BS gets to schedule multiple users, the higher is the probability of multistream transmission in general. Even a significant fraction of users close to the cell edge can be served using spectrally efficient multi-stream transmission. We have investigated the performance in an interference-limited environment, and shown that frequency-selective interference knowledge improves the performance by means of optimum combining at the terminal side and yields a more precise estimation of the achievable rates as well. By sharing the same resource among multiple users in a cell, the overall throughput can be enhanced by 68 percent in a cellular  $2 \times 2$  MIMO link compared to the traditional interference-whitening approach. Our real-time implementation shows that the approach is easily introduced in the LTE signal processing chain. We have also tested the scheme in field trials in a typical urban macrocell deployment. Our results confirm that there is a significantly higher benefit of multiple antennas in a cellular network if the mobile terminals are aware of the frequency-selective interference and sharing of resources among multiple users in a cell is enabled.

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