Distributed MIMO Systems with Spatial Reuse for High-Speed Indoor Mobile Radio Access

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Abstract—This paper introduces a system concept for indoor (local area) mobile radio access. By taking advantage of a distributed deployment of multiple antennas at the transmitter and the individual characteristics of the mobile radio channel in indoor scenarios we demonstrate that multiple users may be spatially divided which spares the rare time and frequency resources. This leads to a high spectral efficiency, supporting the large data rates that are expected for this type of scenario. The main innovations of our approach are the combination of a distributed antenna deployment with sophisticated multi-user MIMO schemes, the introduction of spatial pilot reuse to significantly lower the pilot overhead, and the joint optimization of the pilot strategy for both downlink and uplink while keeping the user terminal complexity low.

Realistic system level evaluations demonstrate the spectral efficiency achievable by our proposed system concept even under consideration of many real-world effects such as channel estimation errors and delays, RF impairments, and pilot and signaling overhead.

Index Terms— Multi-User MIMO communication, indoor mobile radio access, Local Area deployment, distributed MIMO, spatial pilot reuse

I. INTRODUCTION

In this paper we propose and evaluate a system concept that shall provide a high-data rate mobile radio access in an indoor area. Possible application scenarios include offices, airports, shopping malls, and other public places.

The mobile radio channel is characterized by a number of specifics in this type of scenario. First of all, the user mobility is rather low, pedestrian speeds of 3-5 km/h are usually not exceeded. This leads to a large coherence time of the channel so that channel knowledge at a decent quality is valid over longer periods of time. Also, the coverage area is limited so that distributed antennas may be deployed since these can easily be linked via optical fibers. Moreover, indoor coverage usually represents an isolated cell so that issues such as intra-cell interference coordination (which usually represent the limiting factor in cellular systems) do not have to be considered. Finally, the rich scattering conditions in indoor radio propagation offer a large amount of spatial diversity enabling the system to separate many users spatially.

The system concept we propose combines all these features to fully exploit the spatial diversity the mobile radio channel offers. The large data rates this concept is able to achieve renders it an attractive approach for future mobile communication systems. The novelty in the contributions within this paper can be summarized as follows: First of all, we propose to employ spatial pilot reuse which lowers the pilot overhead dramatically. Second, we introduce a pilot design that treats the acquisition of channel state information (CSI) at both link ends along with suitable MIMO techniques that operate well at the expected CSI quality level and take advantage of the distributed MIMO deployment. The system design is targeted to enable cheap and simple (mass-market) user terminals. This is accomplished by moving as much of the signal processing tasks as possible to the base station and only using simple schemes at the terminals. Finally, we evaluate the entire system concept in realistic system level simulations including many real-world impairments to demonstrate the spectral efficiency we can expect.

II. INDOOR SCENARIO

The scenario we study is depicted in Figure 1. This “small office” scenario consists of 40 rooms of size 10 m x 10 m and two corridors that are 5 m wide. The users are assumed to be evenly distributed on the entire office floor. Figure 1 also depicts our proposed distributed antenna deployment. Each of the green lines represents one uniform linear array of cross-polarized antennas. All antenna elements are connected to one single base station that may use all of them jointly for transmission. Following the recommendations in [WIN2D6.13.7], we propose to deploy four cross-polarized antenna elements per array with an inter-element spacing of λ / 2. Consequently, the base station can use eight ports for each array which yields a total of 32 antenna elements usable for transmission. The main benefits of the distributed antenna deployment are more even signal power distribution across the coverage area and significantly reduced spatial correlation boosting the potential value of SDMA even further.

Each user terminal can use either a single antenna element or one cross polarized element with two ports. Due to the small distances the total transmit power is limited to 21 dBm both for the base station as well as the user terminals. At the user terminals, isotropic antennas (0 dBi) are assumed whereas the base station antennas have a directivity of 5 dBi. This stems from the fact that they are mounted at the ceiling and therefore only have to cover the area below this point.

The OFDM parameters of the system are shown in Table 1. They follow the recommendations in [WIN2D6.13.7]. The 1840 subcarriers are split into 230 chunks which represent the basic resource element used for
the spatial scheduling. In time direction, each chunk comprises of 15 consecutive OFDM symbols. Therefore, 120 symbols are available within each chunk. For the link adaptation, chunk-wise adaptive modulation and coding based on rate-compatible punctured block low density parity check codes (RCP-BLDPC) with code rates from 1/3 to 4/5 and modulation sizes from BPSK up to 64-QAM are used (cf. Figure 4).

III. TERMINOLOGY AND DATA MODEL

Assuming a perfectly tuned OFDM system without any inter channel interference, the downlink input output data model of the MIMO system with linear precoding and decoding can be expressed in the following way

\[ y = D \left[ H(f,t) \cdot F \cdot x + n \right] \]

where \( D \in \mathbb{C}^{r \times M} \) is a block-diagonal matrix containing the users’ receive filters \( D_k \in \mathbb{C}^{r \times M_k} \), the matrix \( H(f,t) \in \mathbb{C}^{r \times M \times T} \) represents the joint users’ MIMO channel matrix at frequency \( f \) and time \( t \), \( F = [F_1, \ldots, F_K] \in \mathbb{C}^{M \times K} \) denotes the overall precoding matrix and the vectors \( x, y, \) and \( n \) represent the vectors of transmitted symbols, received symbols, and additive noise at the receive antennas, respectively. The terms \( r \) and \( M_k \) denote the number of data streams and the number of antennas at the \( k \)-th user terminal, whereas \( r, M_k \), and \( M_T \) symbolize the total number of streams, receive antennas, and transmit antennas. The task of the precoding matrix \( F \) is to transform the MIMO channel matrix into a block diagonal matrix, i.e., to mitigate multi-user interference (while balancing it with noise enhancement). The decoding matrices \( D_k \) serve to combine the signals of the users’ antennas efficiently. Our investigations have shown that in the investigated scenario even for two-antenna terminals, a second data stream is not reliable enough for data transmission. We therefore propose to transmit a single stream per user (\( r_e = 1 \)) using dominant eigenmode transmission (DET).

Pilots transmitted after applying the precoding are termed downlink dedicated pilots per layer. They are dedicated because the precoding is user-specific. Pilots transmitted without precoding are termed downlink common pilots. They are common because every user can receive them. Pilots transmitted from the user terminals in the uplink are termed uplink dedicated pilots; they are dedicated because only one user can transmit a pilot at a time.

IV. MULTI-USER MIMO SYSTEM CONCEPT

A. Acquisition of channel state information (CSI)

For the downlink transmissions our goal is to exploit the spatial diversity of the mobile radio channel along with the large number of antennas to serve a large amount of users at the same time and frequency resources through spatial reuse schemes. To achieve this goal, the base station requires instantaneous channel state information (CSI) of the MIMO channel between all base station antennas and all of the user antennas. One possible way would be to let the user terminals estimate their own channels during the downlink transmissions and use feedback to signal this information back to the base station. This strategy is disadvantageous due to a number of reasons: a) The additional effort we have to spend at the user terminals is undesirable, we would like to move as much computational cost as possible to the base station to make user terminals cheap and low in power consumption; b) The uplink data rate is reduced by the feedback rate which is undesirable since the uplink data rate is already the bottle neck of the system; c) the feedback delay degrades the quality of the CSI which is anyways low due to the expected heavy quantization; d) the acquisition of the unweighted channel to each base station antenna requires common pilots per antenna in the downstream which implies a large pilot overhead. We therefore focus on an alternative approach which is the exploitation of channel reciprocity. Since time division duplexing (TDD) is assumed, the same frequency resources are used for the down- and uplink transmissions. We can therefore extract downlink CSI from the uplink transmissions of the user terminals. To achieve this, each user needs to transmit dedicated pilots per antenna in the uplink. However, this overhead is comparably small since the user terminals are only equipped with one or two antennas. From each pilot transmission, the base station can acquire the channel coefficients to all its antennas at the same time. This channel state information is then used for the downlink transmissions, assuming channel reciprocity. Moreover, it can also be used to decode the users’ uplink data transmissions at the base station.

It should be noted that the available CSI is erroneous due to channel estimation errors, channel instationarity (outdated CSI), and due to RF impairments limiting the validity of the reciprocity we are exploiting. The spatial reuse scheme we choose should therefore be able to operate also in presence of imperfect CSI. It has been shown in the literature that linear precoding and decoding schemes are significantly more robust against CSI impairments [SHGJ06]. Considering realistic models for the RF impairments our investigations showed that most non-linear schemes fail completely. We therefore propose to use linear precoding and decoding schemes. In particular, Successive MMSE precoding [SH04] as well as Regularized Block Diagonalization [SH08] are promising candidates that were shown to be able to extract the full diversity of the MIMO channel. These schemes can be used as precoding schemes that block-diagonalize the MIMO channel as well as for separating the data streams from multiple users’ uplink transmissions [SH05].

Concerning the other link end our system concept is
designed in such a way that the user terminal requirements are low to enable cheap mass market devices. For the uplink data transmissions we therefore propose to use open loop techniques such as Alamouti space-time block coding, which is well suitable for two-antenna terminals and does not require any CSI. Finally, to decode the downlink transmissions from the base station, our proposal is to use an MMSE (also known as interference rejection combination, IRC) receiver. To tune the MMSE filter coefficients, the user terminal needs knowledge of its effective channel, i.e., the channel to this user terminal after the precoding. This information can be acquired by inserting dedicated pilots per layer into the downlink transmissions.

Previous system proposals usually included the requirement that dedicated pilot transmissions must be made orthogonal, i.e., symbols used for pilot transmissions to one user must be reserved (filled with zero) in the chunks of all other users. This leads to the undesirable consequence that the pilot overhead grows linearly with the number of users that are spatially multiplexed, eventually rendering large SDMA groups infeasible. Our investigations have shown that we can transmit dedicated pilots to several users at the same time and frequency resources, i.e., to employ spatial pilot reuse. This leads to some amount of multi-user interference on the pilot symbols and hence degrades the CSI quality. But since the spatial separation in this scenario is very good this degradation is rather minor.

We therefore propose to reserve a fixed number of symbols in each chunk (e.g., 4 or 8) and to fill these with pilot symbols in each spatial layer. An important consequence of this design is that the pilot overhead for both downlink and uplink transmissions is independent of the number of base station antennas. This enables the deployment of a large number of antennas to fully exploit the spatial diversity the propagation conditions offer.

B. Downlink system concept

For the downlink transmissions, the following steps are required:

- From UT uplink pilot transmissions, estimate the channel between the UT and all BS antennas.
- For each chunk in frequency direction compute an effective user channel per chunk. If several pilots per chunk are available there are two options: Either compute one estimate for the channels from all pilots and then interpolate between these estimates for every symbol in the chunk. Then to obtain a representative channel for the chunk we factor the average correlation matrix in the following fashion

\[ \tilde{R}_k = \frac{1}{T \cdot F} \sum_{f=1}^{T} \sum_{t=1}^{F} \tilde{H}_k(f,t)^H \tilde{H}_k(f,t) \]

\[ \tilde{R}_k = U_k \cdot A_k \cdot U_k^H \Rightarrow \tilde{H}_k = (A_k)^{1/2} \cdot U_k^H \]

where \( \tilde{H}_k(f,t) \) is the estimate for the channel of the \( k \)-th user at frequency bin \( f \) and OFDM symbol \( t \) and \( F \) and \( T \) represent the number of subcarriers and OFDM symbols within one chunk.

- Based on these effective channels the next step is the spatial scheduling. Here we assign the \( K \) users into smaller groups that we serve in the same chunk via SDMA. The task of the scheduler is to find groups of users that can be spatially well separated. An attractive approach for this task is the ProSched algorithm [FGM07], a low-complexity scheduler based on projections and a tree-based greedy group search. Also, ProSched can take fairness constraints into account.

- Now we can compute the precoding matrices \( F \) for each chunk. Their task is to mitigate multi-user interference between the users scheduled in the same chunk while balancing it with the noise enhancement. Robust and yet very powerful linear precoding schemes are the Successive MMSE (SMMSE) precoding [SH04] or the Regularized Block Diagonalization (RBD) scheme [SH08]. They can also be computed on the effective channels per chunk.

- Transmit data and pilots on the equivalent channel, i.e., the channel after precoding

\[ H_{eq}(f,t) = F \cdot H(f,t) \in \mathbb{C}^{M_r \times T} \]. Ideally, this channel is block-diagonal. Even though there is a residual amount of multi-user interference, pilots for different users can be transmitted at the same time/frequency symbols, via spatial pilot reuse.

- At the user terminals estimate the equivalent channel for the \( k \)-th user \( H_{eq}^{k \rightarrow k} \in \mathbb{C}^{M_r \times T} \) from the downlink dedicated pilots. Note that for two-antenna terminals receiving a single data stream, only two coefficients have to be estimated.

- Tune the MMSE receive filter \( D_k \) based on the latter estimate and use it to receive the data.

C. Uplink system concept

Similar to the downlink, the uplink data transmission chain requires the following steps:

- As before, the required CSI at the base station is obtained from the users’ uplink pilot transmissions.
- Again, the user groups are selected at the base station which signals the user terminals which resources they

### Table 1: OFDM Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>carrier frequency</td>
<td>5 GHz</td>
</tr>
<tr>
<td>guard interval</td>
<td>2 µs</td>
</tr>
<tr>
<td>useful symbol duration</td>
<td>20.48 µs</td>
</tr>
<tr>
<td>subcarrier spacing</td>
<td>44828.125 Hz</td>
</tr>
<tr>
<td>total bandwidth</td>
<td>100.0 MHz</td>
</tr>
<tr>
<td>system bandwidth</td>
<td>89.84 MHz</td>
</tr>
<tr>
<td>used subcarriers</td>
<td>[-920:+920]</td>
</tr>
<tr>
<td>chunk size</td>
<td>8 subcarriers, 15 OFDM symbols</td>
</tr>
<tr>
<td>duplexing mode</td>
<td>TDD</td>
</tr>
<tr>
<td>duplexing guard time</td>
<td>8.4 µs</td>
</tr>
<tr>
<td>effective chunk duration</td>
<td>0.3456 ms</td>
</tr>
</tbody>
</table>
may use for transmission.

- At the user terminals, use Alamouti space-time block coding for the transmission. This does not require any channel state information.
- At the base station, use linear multi-user detection schemes to separate the transmissions of the users. Again, SMMSE as well as RBD can be used for this task [SH05]. After the multi-user interference has been suppressed, decode the Alamouti transmissions using the equivalent channel after decoding (i.e., assuming parallel single-user channels).

V. SYSTEM PERFORMANCE EVALUATION

To evaluate the spectral efficiency of our proposed system concept, system level simulations have been performed. The system parameters are chosen as described in Section II. The multi-user MIMO channels have been generated by the WIM2 channel model [WIN2D1.1.2], which is an extension of the SCME [BSGMKH05]. To make the simulation feasible, the bit level procedures have not explicitly been simulated but mapped using a mutual information based link to system interface [WIN2D2.2.3]. The mapping curve is shown in Figure 4, where the Shannon capacity is also plotted as a reference. Note that the SINR operating region is between -3 dB (below which communication is not possible) and +17 dB (above which the UTs cannot make use of any additional signal power).

For the CSI imperfections, a channel estimation error has been modeled according to [WIN2D6.13.7]. Moreover to account for violations of the reciprocity assumed for the downlink transmissions, RF impairments have been modeled according to the self-calibration approach described in [BCK03].

In Figure 2 and Figure 4, the downlink system level simulation results are shown. ProSched has been used for spatial scheduling. Two versions of the scheduler are shown: The “MaxTP” curves represent the user groups that maximize the total sum rate of the system, i.e., no fairness constraints are included. On the other hand for the “PF” curves a proportional fairness constraint has been included. Comparing the approaches we note that the overall sum rate gets reduced by including the fairness. On the other hand, the improved fairness can be seen from the user throughputs where for the MaxTP option some users do not get served at all. Note that spectral efficiencies in the range of 40-50 Bits/s/Hz can be achieved and that around 80% of the users are served with more than 50 MBit/s. These figures do account for CSI impairments as well as the overhead in terms of signalling and pilots. For this simulation, eight symbols were reserved in each chunk for the downlink dedicated pilots and an additional twelve symbols for signalling and control information. Also overhead from guard bands, guard intervals, and superframe preambles was considered.

The uplink simulation results are depicted in Figure 5 and Figure 6. For simplicity we have considered round robin scheduling with a fixed group size of 13 users per chunk. We show the performance of SMMSE and RBD receivers in comparison to applying no spatial reuse (TDMA/FDMA). Also the impact of CSI imperfections is depicted by adding the theoretical system performance that assumes perfect CSI. The spectral efficiency is lower than on the downlink but with 30-40 Bits/s/Hz still considerably high. From the user throughputs we can see the effect of the round robin scheduling: While the peak throughput is only 140 MBit/s, around 95 % of the users enjoy a data rate of more than 50 MBit/s. As before, these figures do account for pilot and signaling overhead.

Figure 2 – CCDF of cell spectral efficiency for the downlink using SMMSE/RBD precoding vs. no spatial reuse (TDMA/FDMA), ProSched for spatial scheduling without fairness (MaxTP) and with proportional fair option (PF).

Figure 3 – Link to system mapping for the rate-compatible punctured block low density parity check codes, considering 10 combinations of modulation size and code rate (1/3 to 4/5, BPSK to 64-QAM).

Figure 4 – CCDF of user throughput for the downlink using SMMSE/RBD precoding vs. no spatial reuse (TDMA/FDMA), ProSched for spatial scheduling without fairness (MaxTP) and with proportional fair option (PF).
Figure 5 – CCDF of cell spectral efficiency for the uplink using Alamouti and SMMSE/RBD decoding vs. no spatial reuse (TDMA/FDMA), Round Robin scheduling with group size 13. For comparison, the performance with perfect CSI is shown.

Figure 6 – CCDF of user throughput for the uplink using Alamouti and SMMSE/RBD decoding vs. no spatial reuse (TDMA/FDMA), Round Robin scheduling with group size 13. For comparison, the performance with perfect CSI is shown.

VI. CONCLUSION

In this paper, a system concept for indoor mobile radio access with distributed antennas and spatial reuse is described and evaluated. Our proposal combines some of the individual features of the radio channel in this type of setup such as rich spatial diversity, long coherence times, and small coverage areas. Using a suitable pilot design that possesses a pilot overhead independent of the number of transmit antennas we can reach very high spectral efficiency values while keeping the user terminals simple. This is also due to the deployment of a large number of antennas together with the use of sophisticated linear multi-user precoding schemes. These are robust also against imperfect CSI which is present due to channel estimation errors and delays as well as RF impairments, violating the reciprocity assumption.

Realistic system level simulations demonstrate the capability of our proposed system concept. These simulations do consider pilot and signaling overhead as well as the aforementioned sources of CSI impairments.

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