SOFT HANDOVER IN ADAPTIVE MIMO-OFDM CELLULAR SYSTEM WITH COOPERATIVE PROCESSING

Antti Tölli, Marian Codreanu and Markku Juntti
Centre for Wireless Communications, University of Oulu
P.O. Box 4500, 90014 University of Oulu, Finland *

ABSTRACT
The joint cooperative processing of transmitted signal from several multiple-input multiple-output (MIMO) base station (BS) antenna heads is considered for users located within a soft handover (SHO) region. Downlink space-frequency bit and power allocation problem with different BS power constraints is studied for the considered adaptive MIMO-OFDM system. The performance of the proposed heuristic loading method is shown to be close to the optimal convex optimization method with per BS power constraints. It is shown that the highest SHO gains are achieved with a small power imbalance between the received BS powers at low signal-to-noise ratio (SNR), where the achievable rates can be even doubled. On the other hand, the gain from joint processing in SHO quickly diminishes as the imbalance increases, especially at low SNR. Moreover, the results indicate that the joint processing can be even detrimental for the system performance if a coarse phase synchronization between BS antenna head is not guaranteed, as some additional fading on the target SNR values is introduced.

1. INTRODUCTION
Recently, there has been some research devoted to optimizing the mutual information of a multiple-input multiple-output (MIMO) system with cooperative processing between base stations (BS). For example, [1–4] studied the downlink sum rate and spectral efficiency optimization for MIMO cellular systems with perfect data cooperation between base stations. All theoretical studies above assumed ideally that the inter-cell interference seen at the receiver, the channel and transmitted covariance matrices from all the base stations were perfectly known at and shared between the transmitter(s). However, the required signalling feedback and/or practical channel estimation limitations would make the ideal approach unpractical in most applications.

In a time division duplex (TDD) orthogonal frequency division multiplexing (OFDM) system with adaptive MIMO transmission, the modulation parameters in uplink (UL) and downlink (DL) can be adapted according to the channel conditions. The reciprocal DL channel can be estimated accurately during the previous UL frame assuming that the frame length is shorter than the channel coherence time. In order to attain the channel information between all users and BS antennas in the cellular network the channels should be jointly estimated at each BS antenna head. In practical adaptive MIMO–OFDM cellular systems, however, UL transmissions from adjacent cells can be much more attenuated compared to the own cell users, thereby, the joint channel estimation may be difficult if not impossible to implement in practice.

We consider somewhat more practical case where the joint cooperative processing of the transmitted signal from several MIMO BS antenna heads is restricted to an area where the users have comparable signal strengths from adjacent BS antenna heads. Moreover, we assume that the cooperative signal processing can be performed in a centralized manner so that the MIMO antenna heads are distributed over a larger geographical area (e.g. hundreds of meters). The distributed antenna heads are then connected to the central processing unit (controller) via radio over fibre technology or wireless microwave links, for example. Similarly to the soft handover (SHO) feature in (W)CDMA systems [5], SHO region is defined for users with similar received power levels from adjacent distributed BS antenna heads (±3 dB SHO window, for example). Since the signal processing of the BS antenna heads is concentrated at one central controller, joint beamforming from all the antennas belonging to the "active set" can be performed to the user(s) within the SHO region. The transmissions for other users outside the SHO region are seen as interference. In the following, the distributed BS antenna heads are denoted as base stations, for simplicity.

In this paper, we concentrate on DL space-frequency bit and power allocation problem with different BS power constraints for the considered adaptive MIMO-OFDM system. Optimal power allocation with per BS power constraints using convex optimization tools is derived and compared to a more practical but sub-optimal heuristic power allocation. The performance of cooperative processing is studied both in terms of the mutual information and more practical achievable spectral efficiency per user. In order to perform joint transmission from all the BSs belonging to the active set, the baseband signals need to have a common carrier phase reference and the impact of the propagation delay from each of the transmitters to the intended user must be fully compensated for at the transmitter by using some feedback from terminals, for example. The impact of imperfect synchronization between the BS antenna heads on the achievable gains is also addressed with some practical examples. The emphasis is put on providing methods for throughput maximization of the users in a single SHO active set while the system level gains and trade-offs from cooperative SHO processing will be investigated further in [6]. The impact of the size of the SHO region, overhead from increased hardware and physical (time, frequency) resource utilization, different non-reciprocal inter-cell interference distributions due to SHO must be evaluated by system level simulations.

*This research was supported by Finnish Funding Agency for Technology and Innovation (TEKES), Nokia, the Finnish Defence Forces, Elektrobit, Tauno Töning Foundation, Nokia Foundation and Infotech Oulu Graduate School.

1-4244-0330-8/06/$20.00 ©2006 IEEE
II. SYSTEM MODEL

The cellular adaptive MIMO-OFDM system consisting of $N_B$ base stations has $N_C$ sub-carriers, each BS has $N_T$ transmit antennas and user $k$ is equipped with $N_R_k$ receive antennas. A user is served by $M_k$ BSs which define the SHO active set $S_k$ for the user $k$. The signal vector $y_{k,c} \in \mathbb{C}^{N_{R_k}}$ received by the user $k$ at the subcarrier $c$ can be expressed as

$$y_{k,c} = \sum_{b \in S_k} a_{b,k} H_{b,k,c} (x_{b,k,c} + \sum_{\forall i \neq k} x_{i,b,c}) + \sum_{b \notin S_k} a_{b,k} H_{b,k,c} x_{b,c}^* + n_{k,c}$$

where $x_{b,k,c} \in \mathbb{C}^{N_{T_b}}$ is the transmitted signal from the $b$'th base station to user $k$, $x_{b,c}^* \in \mathbb{C}^{N_{T_b}}$ denotes the total transmitted signal vector from BS transmitter (TX) $b$, $n_{k,c} \sim \mathcal{CN}(0, N_0 I_{N_{R_k}})$ represents the additive noise sample vector, and $a_{b,k} H_{b,k,c} \in \mathbb{C}^{N_{R_k} \times N_{T_b}}$ is the channel matrix from BS $b$ to user $k$ with large scale fading coefficient $a_{b,k}$. The elements of $H_{b,k,c}$ are normalized to have unitary variance.

The signal $\tilde{x}_{k,c} = [x_{S_1(1),k,c}, \ldots, x_{S_{M_k}(M_k),k,c}]^T \in \mathbb{C}^{M_k N_{T_k}}$ transmitted for user $k$ is distributed over $M_k$ base stations being in SHO active set $S_k$. The global channel matrix $\tilde{H}_{k,c} \in \mathbb{C}^{M_k N_{T_k} \times N_{R_k}}$ for user $k$ from all $M_k$ BSs is defined as

$$\tilde{H}_{k,c} = [a_{S_1(1),k} H_{S_1(1),k,c}, \ldots, a_{S_{M_k}(M_k),k} H_{S_{M_k}(M_k),k,c}]$$

The vectors $i_{k,c}^{\text{intra}} = \sum_{b \in S_k} a_{b,k} H_{b,k,c} x_{b,c}^*$ and $i_{k,c}^{\text{inter}} = \sum_{b \notin S_k} a_{b,k} H_{b,k,c} x_{b,c}^*$ include the received intra- and inter-cell interference, respectively.

The transmitted vector for user $k$ is generated as $\tilde{x}_{k,c} = M_k x_k$ where $M_k \in \mathbb{C}^{N_{T_k} \times N_{S_k}}$ is the precoding matrix, $d_{k,c} = [d_{k,c}, \ldots, d_{m_{k,c},k,c}]^T$ is the vector of normalized complex data symbols transmitted at subcarrier $c$, and $m_{k,c} \leq \min(N_{T_k} M_k, N_{R_k})$ denotes the number of active data streams. The received signal at subcarrier $c$ by the user $k$ can be expressed compactly as:

$$y_{k,c} = T_{k,c} d_{k,c} + i_{k,c}^{\text{intra}} + i_{k,c}^{\text{inter}} + n_{k,c}$$

where $T_{k,c} = \tilde{H}_{k,c} M_k$. Represents the equivalent channel matrix of the user $k$ at subcarrier $c$.

The receiver (RX) is assumed to be equipped with a linear minimum mean square error (LMMSE) filter and the decision variables are generated as $d_{k,c} = W_{k,c}^H y_{k,c}$. The weight matrix $W_{k,c} \in \mathbb{C}^{N_{S_k} \times m_{k,c}}$ of the LMMSE filter is found by a minimization

$$W_{k,c} = \arg \min_{W_{k,c}} E \left[ ||d_{k,c} - W_{k,c} y_{k,c}||^2 \right]$$

and is given as

$$W_{k,c}^H = T_{k,c}^H (T_{k,c} T_{k,c}^H + Z_{k,c} + R_{k,c})^{-1}$$

where $Z_{k,c}$ and $R_{k,c}$ are the intra-cell interference and the inter-cell interference-plus-noise covariance matrices, respectively.

Note that, in practical adaptive MIMO-OFDM cellular systems, the ideal knowledge of $R_{k,c}$ at the transmitter in addition to the receiver would require it to be reported to the transmitter for each subcarrier and for each transmitted data frame. See [7] for more details. In this paper, however, we assume that the $R_{k,c}$ is fully known at the transmitter while the practical interference scenarios are considered in the system level study [6].

III. COOPERATIVE PROCESSING IN SHO

A. Single User Transmitter Design

The instantaneous mutual information of the single user MIMO-OFDM [bit/s/Hz] link ($Z_{k,c} = 0$) is given by

$$I_k^{\text{(inst)}} = \frac{1}{N_C} \sum_{c=1}^{N_C} \log_2 \left| I + R^{-\frac{1}{2}}_{k,c} \tilde{H}_{k,c} C_{k,c} \tilde{H}_{k,c}^H R_{k,c}^{-\frac{1}{2}} \right|$$

where $C_{k,c} = E \left[ \tilde{x}_{k,c} \tilde{x}_{k,c}^H \right] = M_k x_k M_k^H \in \mathbb{C}^{N_{T_k} m_{k,c} \times N_{T_k} m_{k,c}}$ is the covariance matrix of the signal transmitted on the $c$'th sub-carrier.

Ideally, with both $\tilde{H}_{k,c}$ and $R_{k,c}$ known at the transmitter, the optimum pre-coder $M_k x_k$ which maximizes (5), is given by $M_k x_k = V_{k,c} P_{k,c}^{1/2}$, where $V_{k,c} = [v_{k,c,1}, \ldots, v_{k,c,m_{k,c}}]$ contains the first $m_{k,c} = \text{rank}(\tilde{H}_{k,c})$ columns of unitary matrix $\tilde{V}_{k,c}$, which is obtained by singular value decomposition (SVD) of the pre-whitened channel matrix $\tilde{H}_{k,c}^w = R_{k,c}^{-1/2} \tilde{H}_{k,c} = \tilde{U}_{k,c} \tilde{\Lambda}_{k,c}^{1/2} \tilde{V}_{k,c}^H$ [1, 8]. In this way, a set of $m_{k,c}$ orthogonal spatial sub-channels are obtained at each sub-carrier and the diagonal matrix $P_{k,c} = \text{diag} \left( P_{k,c,1}, \ldots, P_{k,c,m_{k,c}} \right)$ controls the powers allocated for each of the $m_{k,c}$ eigenmodes. The diagonal matrix $\Lambda_{k,c} = \text{diag} \left( \lambda_{k,c,1}, \ldots, \lambda_{k,c,m_{k,c}} \right)$ includes the first $m_{k,c}$ eigenvalues of the Hermitian matrix $\tilde{H}_{k,c}^H R_{k,c}^{-\frac{1}{2}} \tilde{H}_{k,c}$. The transmit covariance matrix becomes $C_{k,c} = V_{k,c} P_{k,c} V_{k,c}^H$ and (5) can be simplified to

$$I_k^{\text{(inst)}} = \frac{1}{N_C} \sum_{c=1}^{N_C} \sum_{i=1}^{m_{k,c}} \log_2 (1 + \lambda_{k,c,i} P_{k,c,i})$$

which is maximized with respect to $P_{k,c,i}$ subject to different power constraints in the next section.

B. Power Optimization for Cooperative BS Processing

Different power constraints can be considered for cooperative BS processing [2, 4]. In this section, we provide the power allocation for maximizing the mutual information (6) under two general power constraints: a sum power constraint for all $M_k$ BSs in the SHO active set $S_k$ and an individual power constraint for each BS.

Under the sum power constraint, $P_{\text{sum}}$, the mutual information (6) is maximized by the well known water-filling power allocation [9], $P_{k,i,c} = \left( \mu - 1/\lambda_{k,i,c} \right)^+$, where the "water level", $\mu$, is chosen such that the sum power constraint holds with equality, i.e., $\sum_{c=1}^{N_C} \sum_{i=1}^{m_{k,c}} P_{k,i,c} = P_{\text{sum}}$. 

The 17th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC’06)
We now focus on the per BS power constraint. The total power transmitted by the BS $S_k(n)$ is

$$\sum_{c=1}^{N_C} \text{Tr} \left( E[S_k(n),c][S_k(n),c]^H \right) = \sum_{c=1}^{N_C} \sum_{i=1}^{m_{k,c}} \|v_{k,i,c}\|^2_2 P_{k,i,c} \tag{7}$$

where $M_{k,c}(n) \in \mathbb{C}^{N_T \times m_{k,c}}$ is the pre-coder matrix of user $k$ that corresponds to $n$’th base station belonging to $S_k$, i.e., $M_{k,c}(n) = [M_{k,c}[(n-1)N_T+1:nN_T,:]]$, $n = 1, \ldots, M$. Similarly, $v_{k,i,c}$ is the transmit vector for the $i$’th stream of user $k$ that corresponds to $n$’th base station belonging to $S_k$. Based on (7) the problem of maximizing the mutual information in (6) under the per BS power constraint can be formulated as

$$\text{maximize } N_C^{-1} \sum_{c=1}^{N_C} \sum_{i=1}^{m_{k,c}} \log_2 \left( 1 + \lambda_{k,i,c} P_{k,i,c} \right) \quad \text{s.t. } \sum_{c=1}^{N_C} \sum_{i=1}^{m_{k,c}} \|v_{k,i,c}\|^2_2 P_{k,i,c} \leq P_n, \forall n, P_{k,i,c} \geq 0, \forall i,c \tag{8}$$

where the variables are $P_{k,i,c}, i = 1, \ldots, m_{k,c}, c = 1, \ldots, N_C$ and $P_n$ is the power constraint on the BS $S_k(n)$. It is easy to observe that the objective function of (8) is concave and all the inequality constraints are affine. Thus, the problem (8) is a convex optimization problem. More precisely, it is an analytic centering problem [10, Chapt. 8.5.3], and it can be efficiently solved numerically by using standard optimization software packages, e.g., CVX [11].

Inspired by the earlier work in [4], we also provide a simple heuristic algorithm which find a suboptimal, but still efficient, power allocation for the problem (8). Similarly to the sum power constraint case, we impose a water-filling power allocation, $P_{k,i,c} = (\bar{\mu} - 1/\lambda_{k,i,c})^+$, but the water level $\bar{\mu}$ is increased until one of the BSs reaches its power constraint. The water level can be efficiently found by using a bisection method [10], where in each iteration we simply check all the per BS power constraints. In the case of equal power constraints for all the BS, i.e., $P_n = P_T, n = 1, \ldots, M$, the final TX power is allocated such that the BS with strongest reception at the receiver is using the full power $P_T$ while the other BSs are using power less than $P_T$. It will be shown in Section IV. that the heuristic method results in almost the same mutual information as (8).

### C. Bit and Power Loading

Previous sections dealt with maximizing the mutual information with different power constraints. In practical systems, the finite granularity imposed by the finite set of modulation and coding schemes (MCS) makes the bit and power loading optimization problems non-convex, and solutions similar to (8) are difficult if not impossible to obtain. We consider greedy bit and power loading algorithms that try to maximize the achievable spectral efficiency for certain quality of service criteria, such as target frame error rate (FER). In order to guarantee the per BS power constraints, the same heuristic solution as in the previous subsection is proposed. Basically, the only difference to an original single link algorithm, such as the Hughes-Hartogs algorithm [12], is that the per BS power constraints, which are function of $v_{k,i,c}$ as in (7), are included in the stopping criterion. Similarly to the previous section, the iterative process (bit and power loading) is continued until one of the BSs in $S_k$ reaches its power constraint.

In the numerical evaluation we use a low complexity bit and power loading algorithm requiring a low signalling overhead (LSO) [13]. The throughput degradation to the optimal Hughes-Hartog (HH) algorithm for a fixed target frame error rate (FER) was shown to be negligible while the signalling overhead was $N_C$ times reduced. See [13] for more details.

### D. Multiuser SDMA for SHO

The main focus in previous sections was on the cooperative processing for single user transmission. However, the users having identical SHO active set composition can be served in the same time-frequency transmission slot using some space division multiple access (SDMA) method to separate them in space domain [2, 14]. SDMA can be used to improve the utilization of the physical resources (space, time, frequency) by exploiting the available spatial degrees of freedom in downlink multi-user MIMO channel, with an expense of somewhat increased complexity. In general, the transmitters can send up to $MN_T$ data streams, regardless of the number of users being in the active set, as long as the total number of streams does not exceed the spatial dimensions. This means that $MN_T \geq \sum_k m_{k,c} c$, where $M$ is the active set size common to all $k$ having identical active set composition. These issues will be addressed in more details in [6].

### IV. SIMULATION RESULTS

The simulated OFDM system was based on HIPERLAN/2 [15] and IEEE 802.11a assumptions, where the number of subcarriers in the OFDM air interface is $N_C = 64$ and the cyclic prefix length is 16 samples. The channel delay taps were considered independent of each other with power delay profile specified by ETSI BRAN Channel A [15], and the elements of the channel matrices were modelled as i.i.d. Gaussian random variables. The number of both TX and RX antennas was fixed at 2, $\{N_T, N_{R_k}\} = \{2, 2\}$. For simplicity, we assume that all the base stations have equal maximum power limit $P_T$, i.e., $P_n = P_T \forall n$, and the impact of inter-cell interference is omitted, i.e., $R_{k,c} = N_0 I$. The impact of the following three power constraints is studied:

- **Sum power constraint**: All $M_k$ BSs in $S_k$ have perfect power cooperation in addition to the data cooperation. This provides an unrealistic upper bound, where the pooled maximum available power is always $P_{sum} = M_k P_T$, while the antenna array gain from having $M_k N_T$ transmit antennas depends on the RX power differences between BSs.

- **Per BS power constraint**: Available power can be increased up to $M_k$ times depending on the RX power difference between BSs. Also, the antenna array gain
from having $M_kN_T$ transmit antennas depends on the RX power difference.

- **Shared single BS power constraint**: The same total TX power is used as in the single link case, i.e., $P_{\text{sum}} = P_T$ is shared between $M_k$ BSs and only antenna array gain is available.

## A. Mutual Information

The ergodic mutual information for 2-branch SHO with different power constraints is studied in this section. Fig. 1 illustrates the ergodic mutual information for different power imbalance values $\alpha = \frac{a^2_{S_k(2),k}}{a^2_{S_k(1),k}}$, where $S_k(1)$ is the BS with the strongest reception at the terminal, and for 0 dB and 20 dB single link SNRs ($SNR = P_Ta^2_{S_k(1)}/N_0$).

It is seen from the figure that the performance of the proposed heuristic method is close to the optimal convex optimization method (8) with per BS power constraints. It also shows that the gain from joint processing in SHO quickly diminishes as the imbalance between the received BS powers increases, especially at low SNR. On the other hand, the highest SHO gains are achieved at low SNR range, e.g., the achievable rate can be even doubled at 0 dB single link SNR and with 0 dB imbalance between BSs. The achievable rate with sum power constraint provides an unrealistic upper bound assuming that the BSs can share their TX powers. Sum power constraint with infinite power imbalance (-Inf) is equivalent to single link transmission with 3 dB higher SNR.

## B. Link Level Results

In this section, the single user link level performance for 2-branch SHO with different power constraints is studied in terms of achievable spectral efficiency. In the link level simulations, one coded OFDM frame consists of 16 OFDM symbols. Modulation and coding schemes (MCS) in the simulations were QPSK, 16QAM and 64QAM, all turbo encoded and punctured to rate $= 1/2$. The minimum codeword length used in LSO algorithm is $l_{\text{min}} = 500$ bits and the SNRs required by each MCS to achieve the desired target FER=10% in AWGN channel are: 1.8 dB, 7.1 dB and 11.6 dB, respectively. See [13] for more details on LSO algorithm.

Fig. 2 illustrates the achievable spectral efficiency with fixed $-3$ dB power imbalance. With small power imbalance the SHO gains can be rather significant as seen from Fig. 2. But, there is very little gain from SHO at low SNR and with high imbalance between BSs since the TX power is concentrated on the strongest eigenmode(s) only. This can be observed by looking at Fig. 3 where the achievable spectral efficiency is depicted for different power imbalance values and for 0 dB and 12 dB single link SNRs. However, the weaker BS has in general larger contribution on the weaker eigenmode(s). Thus, SHO can provide considerable gains at high SNR even with large imbalance, as the strongest eigenmode(s) become saturated and more power is poured on the weaker eigenmode(s).
C. Impact of non-synchronization between BS antenna heads

The impact of imperfect synchronization between the BSs is illustrated with an example, where joint transmission is carried out from two BSs having a phase mismatch $\varphi$ common to all antenna elements within one BS. In such a case, the estimated channel at the transmitter can be modelled as:

$$\hat{H}_{k,c} = \left[ aS_{k}(1)A_{c}H_{k}(1),k,c, aS_{k}(2)A_{c}e^{j\varphi}H_{k}(2),k,c \right].$$

The transmit pre-coding matrix designed based on the estimated channel is $\hat{M}_{k,c} = \hat{V}_{k,c}^{H}P_{k,c}^{\frac{1}{2}}$, where $\hat{V}_{k,c}$ contains the first $m_{k,c}$ columns of $\hat{V}_{k,c}$ obtained by SVD of $\hat{H}_{k,c} = \hat{U}_{k,c}\hat{\Lambda}_{k,c}\hat{V}_{k,c}^{H}$. Now, SINR $\gamma_{k,i,c}$ per sub-channel at the receiver after receive filtering (4) can be calculated as

$$\gamma_{k,i,c} = \frac{1}{Q_{k,c,i,i}} - 1,$$

where $Q_{k,c,i} = (I + \hat{M}_{k,c}^{H}\tilde{H}_{k,c}^{H}\tilde{R}_{k,c}^{-1}\tilde{H}_{k,c}\hat{M}_{k,c})^{-1}$.

An example in Fig. 4 illustrates the impact of the phase mismatch between two adjacent BS antenna heads for one random channel realization $\{N_{T}, N_{R}, N_{C}, M_{k}\} = \{2, 2, 64, 2\}$, with different RX power imbalance values ($\alpha = aS_{k}(2),k/c/aS_{k}(1),k$) at $P_{T}aS_{k}(1),k/N_{0} = 10$ dB. SINR values per eigenmode after receive filtering are shown for a single sub-carrier as function of phase mismatch. It is clearly seen from the figure that the target SINR values for different MCSs (Section B.) cannot be met at the receiver if there is a phase mismatch between BS antenna heads. However, the phase mismatch can vary between ±60° while the loss in eigenmode SINR is still less than 1.5 dB. The figure also indicates that there would be no gains from joint processing without phase synchronization. On the contrary, some additional fading would be introduced (up to 15dB fades in this example).

V. CONCLUSION

The joint cooperative processing of transmitted signal from several MIMO BS antenna heads is considered for users located within a SHO region. Downlink space-frequency bit and power allocation problem with different BS power constraints is studied for the considered adaptive MIMO-OFDM system. The performance of the proposed heuristic loading method is shown to be close to the optimal convex optimization method with per base station power constraints. It was shown that the gain from joint processing in SHO quickly diminishes as the imbalance between the received BS powers increases, especially at low SNR. On the other hand, the highest SHO gains are achieved at low SNR range with small power imbalance, where the achievable rates can be even doubled. Moreover, the results indicate that there are practically no gains achieved from joint processing if a coarse phase synchronization between BS antenna heads is not guaranteed. On the contrary, some additional fading on the target SINR values is introduced. Even though the single user gains from cooperative SHO processing can be significant the gains and trade-offs must be investigated further by system level simulations.

REFERENCES