MIMO-OFDMA Opportunistic Beamforming with Partial Channel State Information

Issam TOUFIK
Mobile Communications Departement
Institut Eurécom
BP 193, 06904 Sophia Antipolis, France
Email: issam.toufik@eurecom.fr

Hojin KIM
Samsung Advanced Institute of Technology
P.O. Box 111, Suwon, 440-600, Korea
Email: hkim73@samsung.com

Abstract— **Over the past few years, a lot of interest has focused on Orthogonal Frequency Division Multiple Access (OFDMA) and Multiple Input Multiple Output (MIMO) systems thanks to the tremendous gain on system capacity they offer. Transmit beamforming is a low complexity technique that helps in achieving the full diversity afforded by the multiple antenna environment. MIMO-OFDMA systems using opportunistic beamforming are a promising solution to satisfy the growing demand in terms of data rate and Quality of Service (QoS).**

An important practical issue in MIMO-OFDMA systems is the feedback load. As a large number of carriers (e.g. 2048 for WiMax) is usually used in such systems, feeding back full Channel State Information at the transmitter (CSIT) for each carrier is prohibitive. In this paper, the problem of feedback reduction in MIMO-OFDMA opportunistic beamforming is addressed. We present different partial CSIT schemes that reduce significantly the feedback overload at little expense of system throughput.

Index Terms— **MIMO-OFDMA, Beamforming, Multi-user Scheduling, Partial CSI, Feed-back.**

I. Introduction

The promise of future wireless networks is to provide a broad range of multimedia services. Customers are expecting high quality, reliability and easy access to high-speed communications. The use of Multiple Antennas at the transmitter and/or at the receiver (MIMO systems) provides enhancement in system performance without a corresponding increase in bandwidth or transmit power. In the past few years, a great deal of research has been devoted to the combination of this spacial scheme with Orthogonal Frequency Division Multiplexing (OFDM). Such systems combine the advantages of both techniques, providing simultaneously robustness against channel delay spread and increased data rate especially when combined with Dynamic Channel Allocation.

Orthogonal Frequency Division Multiple Access (OFDMA) is an emerging multiple access technology that converts a frequency-selective fading channel into several flat-fading subchannels, exploiting the fact that different users experience different amount of fading at a particular instant of time and scheduling efficiently the data tones to the users. A very important feature of OFDMA is its capability of exploiting the Multiuser Diversity [1], which, combined with dynamic resource allocation, can increase significantly the system throughput, even in the case where hard fairness between active users is required [2], [3].

MIMO systems have emerged as one of the most promising technical breakthroughs in modern wireless communications. The pioneering work by Foschini [4] and Telatar [5] predicted remarkable spectral efficiency for wireless systems using multiple antennas to increase data rates through multiplexing or to improve performance through diversity. The interested reader is referred to [6]. There have been many studies of MIMO systems in multi-user network environment including proposals for scheduling algorithms [7], [8]. One way to exploit multiuser diversity in MIMO systems is through opportunistic beamforming scheduling [9]. In [10], the authors propose a partial feedback scheme exploiting opportunistic multiuser beamforming as a multiuser extension of the opportunistic beamforming initially introduced in [9]. Previous work on opportunistic scheduling has been mainly focused on frequency-flat fading channels. However, in an OFDMA network, only few works have utilized opportunistic schemes to enhance the system throughput. One of the major problems in employing an opportunistic scheme in MIMO-OFDMA systems is the large amount of feedback required to be sent to the transmitter. In [11], the authors proposed an opportunistic scheme, based on the scheme on [9], in which adjacent sub-carriers are clustered into groups and then information on the best clusters is fed back to the base station.

The objective of our work is to propose practical feedback reduction schemes that are more efficient than the obvious extension of the narrowband strategies. In essence, our goal is to reduce the feedback rate without significantly compromising the sum rate performance. In this paper we propose different partial channel state information (CSI) schemes for MIMO-OFDMA combined with opportunistic beamforming. Our method is distinct from that of [11] as we place ourselves in an SDMA context and the best carriers within a cluster are fed back.

The organization of this paper is as follows: Section II presents the underlying system and channel model. In Section III, we present three feedback reduction schemes for the MIMO-OFDMA system. We present the numerical results in Section IV. Finally, in Section V we present our conclusions.

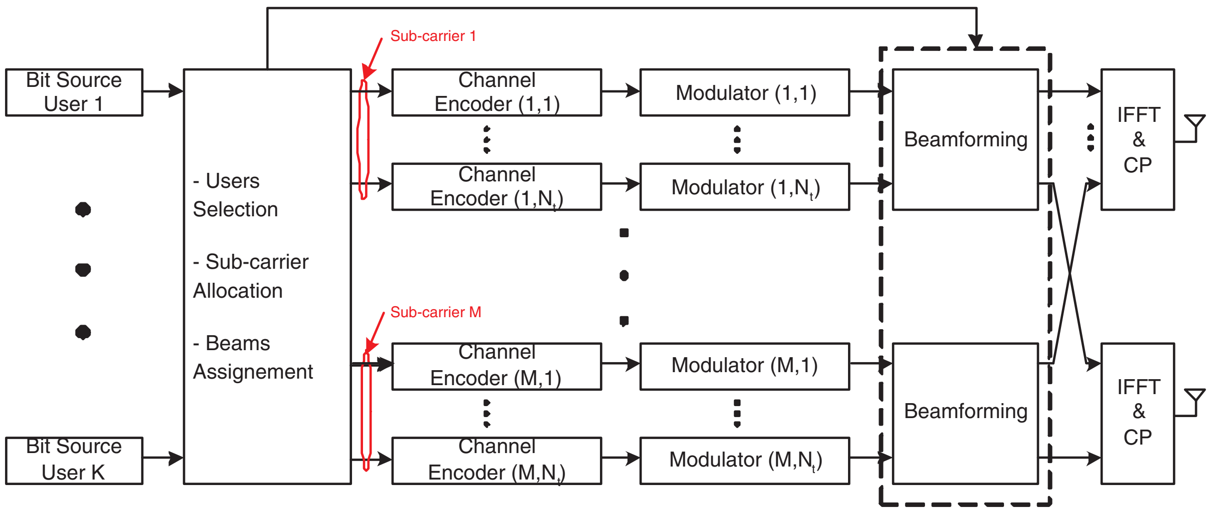

Fig. 1. MIMO-OFDMA Transmitter model

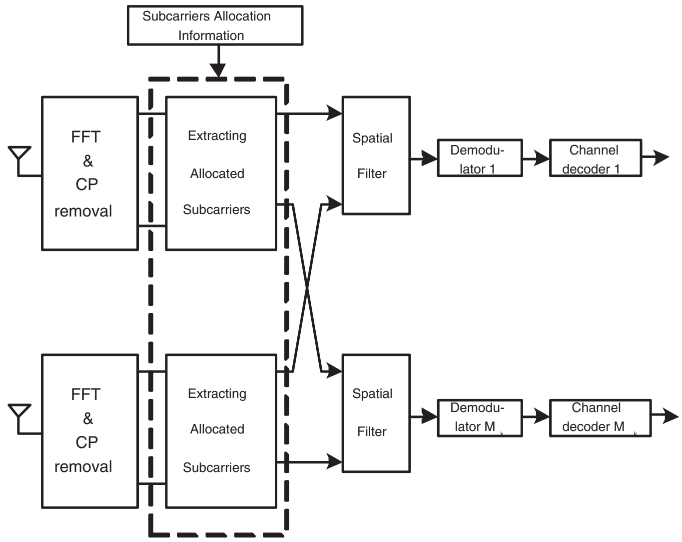

Fig. 2. MIMO-OFDMA receiver model

II. System ans Channel Models

We consider the downlink of a multiuser MIMO-OFDMA system as shown in Fig. 1. The base station (BS) is equipped with N_t transmit antennas and each receiver has N_r receive antennas. Let K denote the number of users and M the number of sub-carriers. A frequency-selective channel is characterized by Γ significant delayed paths. Let $\mathbf{x}[t]$ be the $N_t \times 1$ complex transmitted signal vector and $\mathbf{y}[t]$ the $N_r \times 1$ received signal in the baseband during the t-th signaling interval. Then a discrete-time baseband model can be mathematically described as

$$\mathbf{y}[t] = \sum_{\gamma=0}^{\Gamma-1} \mathcal{H}_\gamma \mathbf{x}[t-\tau_\gamma] + \mathbf{n}[t] \tag{1}$$

where $\mathcal{H}_\gamma$ is an $N_r \times N_t$ matrix representing the γ-th tap of the discrete-time MIMO channel response, and $\mathbf{n}[t]$ is an additive Gaussian noise with zero mean and unit variance. Without loss of generality, we assume that $N_r = 1$ for the remainder of the paper.

Let $\mathbf{H}_{k,m} = [H_{k,m}[1], ..., H_{k,m}[N_t]]^T$ be the $N_t \times 1$ vector of channel gains between transmit antennas and the receive antenna of user k on sub-carrier m. The $H_{k,m}[i]$ denotes the channel gain from transmit antenna i to receiver k and corresponds to the frequency sample, at the frequency corresponding to sub-carrier m, of the multi-path time domain channel impulse response given by

$$h_k[i]\,(t) = \sum_{\gamma=0}^{\Gamma-1} \alpha_\gamma \delta\,(t-\tau_\gamma) \tag{2}$$

where α_γ is the path gain following zero-mean Gaussian distribution with variance σ_γ^2, τ_γ is the delay corresponding to path γ, and Γ is the maximum channel order.

We assume that the channel is invariant during each coded block, but is allowed to vary independently from block to block. The samples of the frequency response are given by

$$H_{k,m}[i] = \sum_{\gamma=0}^{\Gamma-1} \alpha_\gamma e^{-j\frac{2\pi\tau_\gamma f_m}{M}} \tag{3}$$

where f_m is the frequency corresponding to sub-carrier m.

As in [10], random beamforming is used for transmission, i.e., N_t users can be simultaneously scheduled in each sub-carrier. The BS constructs N_t random orthonormal beams $\mathbf{q}_i \in \mathbb{C}^{N_t \times 1}$ for $i = 1, \ldots, N_t$, and the user selection and beam allocation on each carrier can be made jointly depending on the users' feedback. After that, each user's data is mapped to its allocated sub-carriers and bits are coded and modulated. Let $\mathcal{K}_m = \{k_1^m, k_2^m, ..., k_{N_t}^m\}$ be a set of N_t scheduled users on sub-carrier m, such that user k_i^m is assigned the beamforming vector $\mathbf{q}_i$. The transmitted signal on sub-carrier m is then given by

$$\mathbf{x}_m = \sum_{i=1}^{N_t} \mathbf{q}_i s_{k_i^m} \quad (4)$$

where $s_{k_i^m}$ is the modulated symbol of user k_i^m in sub-carrier m. The resulting streams are then transformed to time domain using IFFT and the Cyclic Prefix (CP) is added.
In the receiver (Figure 2) the inverse operations are performed. In each antenna the CP is removed from the received signal and a FFT block is used to transform the signal back to frequency domain. The sub-carriers allocation information fed-back from the BS is used to extract the user signal from its assigned sub-carriers. In each carrier, the signals from different antennas are then combined to retrieve the original transmitted signal.

Assuming that each user can estimate its channel with no error, the signal to interference plus noise ratio (SINR) at receiver k on i-th beam and m-th sub-carrier can be calculated as

$$SINR_{i,k,m} = \frac{|\mathbf{H}_{k,m}\mathbf{q}_i|^2}{N_t/\rho + \sum_{j=1,j\neq i}^{N_t} |\mathbf{H}_{k,m}\mathbf{q}_j|^2} \quad (5)$$

where ρ is the signal-to-noise ratio (SNR), assumed to be the same for each user. The achievable rate of k-th user on i-th beam over sub-carrier m is given by

$$C_{i,k,m} = \log_2 (1 + SINR_{i,k,m}) \quad (6)$$

One of the main problems in MIMO-OFDMA systems is the large amount of feedback required for optimal joint sub-carrier/beam allocation. Since different users can be assigned on different sub-carriers, full channel state information (CSI) on each sub-carrier is needed, which leads to prohibitive feedback load. In the following section, we present different feedback scenarios where each user feeds back only partial CSI for a group of neighboring sub-carriers.

III. Feedback and Scheduling

We consider that the feedback channel is error free and delay free and assume that each receiver has perfect knowledge of the channel in all sub-carriers and for all antennas, but only a partial information on the channel is fed-back to the BS.
We divide the set of available sub-carriers into G groups each one containing a set of L neighboring carriers. Without loss of generality we consider that M is a multiple of G so that each group has the same number of sub-carriers and $L = \frac{M}{G}$.

Let $\{m_l^g\}_{l=1,\ldots,L}$ be the set of L sub-carriers of group g such that m_l^g is the l-th carrier of group g. For each group g and beam $\mathbf{q}_i$, user k should compute a representative rate $\overline{\mathcal{C}}_g(i,k)$ of the set $\left\{C_{i,k,m_l^g}\right\}_{l=1,\ldots,L}$ of achievable rates by users k on beam $\mathbf{q}_i$ over sub-carriers of group g. Let beam $\mathbf{q}_i$ be assigned to user k in sub-carriers of group g, then the BS can transmit at a rate equal to $\overline{\mathcal{C}}_g(i,k)$ in all sub-carriers for which the user's capacity is greater or equal to $\overline{\mathcal{C}}_g(i,k)$ (i.e., sub-carriers such that $C_{i,k,m_l^g} \geq \overline{\mathcal{C}}_g(i,k)$). No transmission will be scheduled on the remaining sub-carriers of the group (i.e., sub-carriers where the user's capacity is less than $\overline{\mathcal{C}}_g(i,k)$) as this will lead to an outage event. Evidently, when the user feeds back the representative capacity, it should also inform the BS about the sub-carriers that can support this rate. The representative value $\overline{\mathcal{C}}_g(i,k)$ is given by

$$\overline{\mathcal{C}}_g(i,k) = \mathcal{F}\left(\left\{C_{i,k,m_l^g}\right\}_{l=1,\ldots,L}\right) \quad (7)$$

where $\mathcal{F}(.)$ is a multi-variable function that depends on the feed-back scenario considered.
Under this configuration, the sum of rate achieved by user k on beam $\mathbf{q}_i$ over the sub-carriers of group g is

$$R_g(i,k) = \mathcal{A}\left(\overline{\mathcal{C}}_g(i,k)\right).\overline{\mathcal{C}}_g(i,k) \quad (8)$$

where $\mathcal{A}\left(\overline{\mathcal{C}}_g(i,k)\right)$ is the number of sub-carriers in group g where user k has a achievable capacity greater or equal to $\overline{\mathcal{C}}_g(i,k)$.

The number of representative values computed by each user for each group is equal to the number of beams N_t. Depending on the feedback reduction scheme, one or a set of these values is fed back to the transmitter.

A simple scheme is one where the representative rate is simply the highest achievable rate over all sub-carriers of the group (This value is supported by only one sub-carrier)

$$\overline{\mathcal{C}}_g(i,k) = \max_{1\leq l\leq L} C_{i,k,m_l^g} \quad (9)$$

The user then feeds-back only the value of the best beam. User also informs the BS of the selected beam and the only sub-carrier where it can support this representative rate. For each carrier, the BS assigns each beam to the user with the highest achievable rate as in [10].

It can be shown that this scheme is asymptotically Optimal (For a number of users $K \rightarrow \infty$) in terms of sum rate. However, for low number of users it is evident that a large number of carriers are not chosen by the users, especially when the number of carriers per group L is large which results in a considerable system performance degradation. This intuitive result calls to investigate more sophisticated feedback schemes where each user has the option to use a larger set of carriers at each group. For that, we propose the following three feed-back strategies.

A. *All **B**eams max-**S**um of rate representative (**ABS**)*

In this scheme, the representative capacity is chosen such that the sum of achievable rates by user k on beam $\mathbf{q}_i$ over the sub-carriers of group g is maximized

$$\begin{aligned}\overline{\mathcal{C}}_g(i,k) &= \arg\max R_g(i,k) \\ &= \arg\max_{C_{i,k,m_l^g}} \mathcal{A}\left(C_{i,k,m_l^g}\right).C_{i,k,m_l^g}\end{aligned}$$

The user estimates the set $\left\{C_{i,k,m_l^g}\right\}_{l=1,\ldots,L}$, of achievable rates on sub-carriers of group g on beam $\mathbf{q}_i$, and sorts its values in increasing order. Let C'_1,C'_2,...,C'_L be the sorted values, then the representative rate is given by

$$\overline{\mathcal{C}}_g(i,k) = \arg\max_{C'_j} (L-j)\, C'_j \tag{10}$$

For each group g, each user feeds back the N_t values $\overline{\mathcal{C}}_g(i,k)$, $i = 1,...,N_t$ and informs the BS on the carriers that can support this rate. Within one group, the users may not use all sub-carriers and can ask for a different set of 'preferred' sub-carriers. Hence, the scheduling must be performed independently for each sub-carrier. Note also that for each sub-carrier, the transmitter assigns the beams to the users that support the highest SINR on these beams as in [10].

B. ***B**est **B**eams max-**S**um of rate representative (**BBS**)*

In this scheme, each user computes the representative capacities, for each group g and beams $\mathbf{q}_i$, in the same manner as in the previous scheme. In the spirit of [10], instead of feeding back the representatives for all beams, each user feeds back only the representative value for its best beam (i.e., the beam with the highest sum rate over the frequencies of the group). For that, the user determines the beam vector $\mathbf{q}_{i^*}$ achieving,

$$i^* = \arg\max_{i=1,\ldots,N_t} R_g(i,k) \tag{11}$$

where $R_g(i,k)$ is given by (8).

The index i^* and the corresponding value $\overline{\mathcal{C}}_g(i^*,k)$ are fed back to the transmitter. Additionally, each user k informs the BS about the sub-carriers that exceed the representative capacity. As in the previous case, for each beam we pick the user that achieves the maximum throughput on that beam.

C. ***B**est **B**eams min-**R**ate representative (**BBR**)*

In the previous schemes, each user informs the BS of the value of the representative rates and should also feed-back the indices of sub-carriers where it can support that rate. This information on the desired sub-carriers can be avoided by chosen a representative rate that can be supported in all sub-carriers of the group. This representative value for beam $\mathbf{q}_i$ is the minimum capacity achieved by the user on this beam over the sub-carriers of group g,

$$\overline{\mathcal{C}}_g(i,k) = \min_{l=1,\ldots,L} C_{i,k,m_l^g} \tag{12}$$

The sum of rate achieved by user k on beam $\mathbf{q}_i$ over the sub-carriers of the group g is then,

$$R_g(i,k) = L.\overline{\mathcal{C}}_g(i,k) \tag{13}$$

For each group g, user k computes the representative values $\overline{\mathcal{C}}_g(i,k)$ for each beam $\mathbf{q}_i$ as given in equation (12). The user then computes for each beam vector $\mathbf{q}_i$, the sum of rate $R_g(i,k)$ given by equation(13). The user then determines the beam vector $\mathbf{q}_{i^*}$ achieving the maximum capacity,

$$i^* = \arg\max_{i=1,\ldots,N_t} R_g(i,k) \tag{14}$$

The beam index i^* and the corresponding value $\overline{\mathcal{C}}_g(i^*,k)$ are fed-back to the BS. Since user k can support the fed-back capacity over all carriers in the group, the feedback concerning the desired carriers is not needed in this scheme.

This alternative offers a considerable reduction in the amount of feed-back but also represents a decrease of the system capacity. The complexity of the allocation process is also reduced. In fact, in the previous schemes, the representative rate is not supported by the user on all sub-carriers of the group and different users express different sets of desired carriers. Thus the scheduling must be done for each sub-carrier individually. In this scheme, the same value of supportable capacity is proposed for all the carriers within the same group. The scheduling is the same for all carriers of the group. This considerably reduces the allocation complexity especially for a large L.

Intuitively, we can predict that for values of L such that the bandwidth of a group of sub-carriers is of the order of the channel coherence bandwidth, the capacity degradation should be very small. The channel variations over sub-carriers within the same group are small and thus the minimum rate in equation (12) is not very different from the optimal rate in (10)

Remark: Additional feedback reduction can be achieved if each user chooses the G' best groups ($G' < G$) and feeds back their CSI instead of feeding back information for all groups. The comparison between groups is made in terms of the users' achievable sum rate over the sub-carriers of the group.

IV. Numerical results

In all simulations of this section, we assumed a system bandwidth of 2.5MHz with 256 equally spaced sub-carriers. We also considered a multi-path channel with an exponentially decaying power delay profile.

Figures 3 and 4 represent the system Spectral Efficiency (SE), for the three feedback reduction schemes, as a function of the number of sub-carriers per group L, for channel delay spread $\tau_{\max} = 2\mu s$ and $\tau_{\max} = 10\mu s$ respectively (i.e. channel coherence bandwidth of the order of 0.5MHz and 0.1MHz). The Number of users is equal to 16 and SNR=0dB. A $2\mu s$ delay spread channel corresponds to a pedestrian environment while the $10\mu s$ delay spread concerns vehicular environment.

It is interesting to note that for a large channel coherence bandwidth ($\tau_{\max} = 2\mu s$), the three schemes have almost the same performances for small to moderate values of L. We also note that the system SE degradation compared to the full feed-back case (ABS feed-back strategy with $L = 1$) is small. In this case, there are only small variations of channel gains over sub-carriers within the same group and the representative rates in equations (10) and (12) are not very different. As expected, when L is large, BBR feed-back strategy suffers a considerable SE degradation.

For small channel coherence bandwidth ($\tau_{\max} = 10\mu s$), ABS and BBS feedback strategies still perform almost the same. BBR strategy suffers from an important system SE degradation.

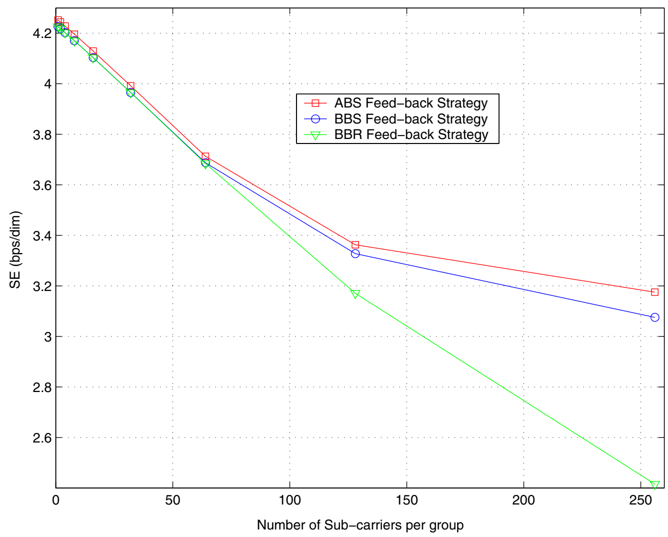

Fig. 3. SE as a function of L. ($\tau_{\max} = 2\mu s$, SNR = 0dB, Nb of users = 16.)

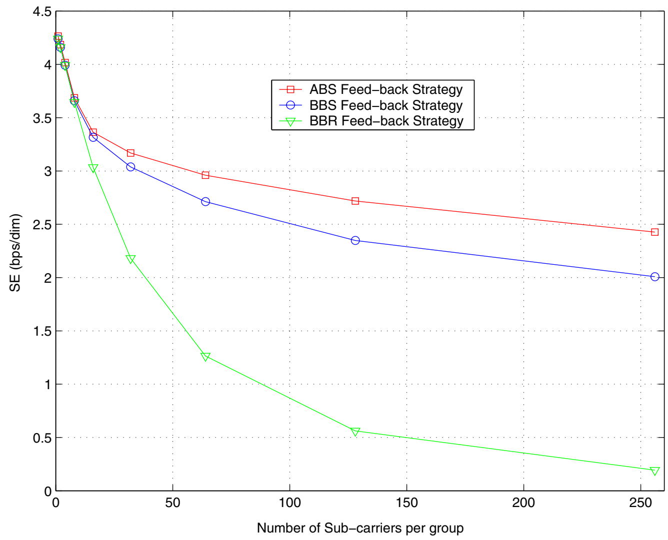

Fig. 4. SE as a function of L. ($10\mu s$, SNR = 0dB, Nb of users = 16.)

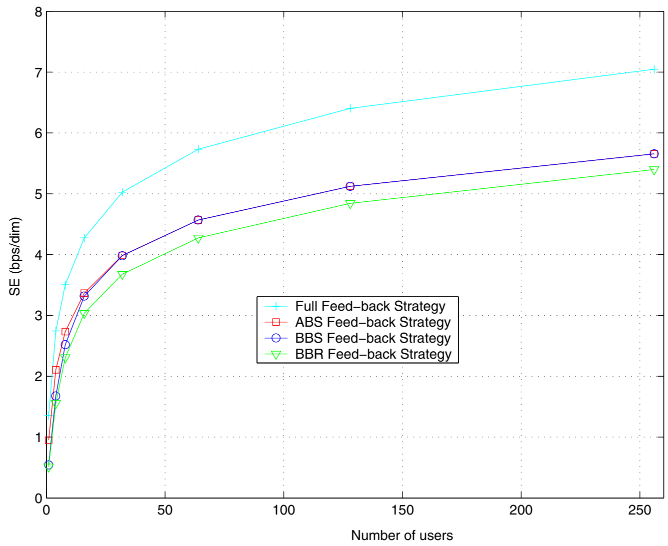

Fig. 5. SE as a function of the number of users. ($\tau_{\max} = 10\mu s$, SNR = 0dB and $L = 16$)

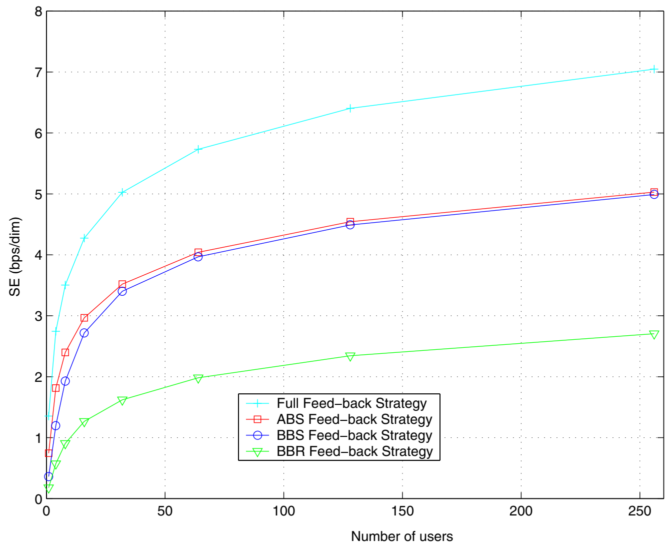

Fig. 6. SE as a function of the number of users. ($\tau_{\max} = 10\mu s$, SNR = 0dB and $L = 64$)

Figures 5 and 6 represent the system SE of the three feedback strategies as a function of the number of users for $\tau_{\max} = 10\mu s$ and for L respectively equal to 16 and 64. The performance of the full feed-back scheme is also given for comparison. We note that for $L = 16$, the three strategies have almost the same performances. Their SE are very close to the full feed-back scheme for small to moderate number of users (sparse network). For $L = 64$, BBR feedback strategy suffers a severe system SE degradation while ABS and BBS strategies still perform the same and have the some performance degradation compared to full feedback scheme.

As we mentioned in the remark of the previous section, additional feedback reduction can be achieved if each user chooses the G' best groups ($G' < G$) and feeds back their CSI instead of feeding back information for all groups. Figure 7 represents the system SE as a function of the number of users for BBS feed-back strategy for different values of G'. We remark that with a reduction of the feedback load by half there is only a very small degradation of the SE of the system. When each user feeds back the CSI for only two groups, the degradation is more severe especially for small number of users (sparse network). The probability that some carriers may not be used is high in this case. This could be solved by employing a power control over the sub-carrier [14].

V. Conclusion

The important issue of feedback reduction in MIMO-OFDMA networks using opportunistic beamforming was addressed here. We proposed and evaluated three practical low

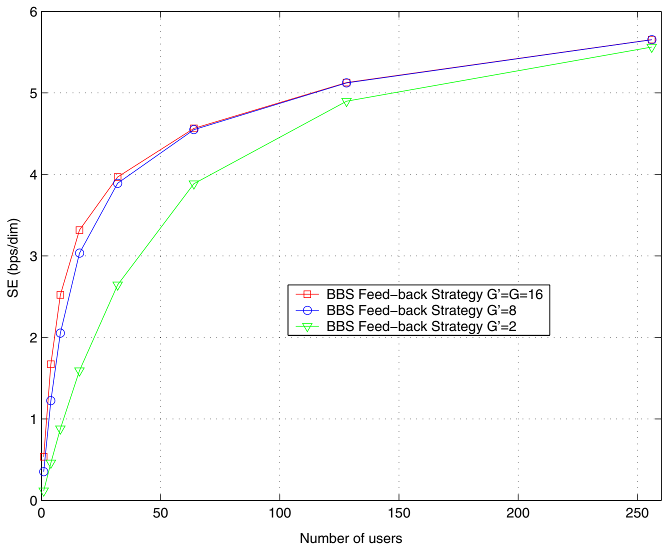

Fig. 7. SE as a function of the number of users. ($\tau_{\max} = 10\mu s$, SNR = 0dB and $L = 16$)

rate feedback schemes that allow to reduce significantly the amount of required CSIT at little expense of system throughput. Our results indicate that MIMO-OFDMA combined with opportunistic scheduling can be a very promising technology for future generation wireless systems.

REFERENCES

[1] R. Knopp and P. A. Humblet, "Multiple-accessing over frequency-selective fading channels," *IEEE PIMRC 1995,*, September 27-29, 1995, Toronto, Canada.

[2] I. Toufik and R. Knopp, "Channel Allocation Algorithms For Multi-carrier Systems," *IEEE VTC2004-Fall. Los Angeles, USA* Page(s):1129 - 1133 Vol. 2. 26-29 Sept. 2004

[3] I. Toufik and R. Knopp, "Multiuser Channel Allocation Algorithms Achieving Hard Fairness," *IEEE GLOBECOM 2004.Dallas, USA* Page(s):146 - 150 Vol.1. 29 Nov.-3 Dec. 2004

[4] G.J. Foschini and M.J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Pers. Commun.,* vol. 6, pp. 311335, Mar. 1998.

[5] E. Telatar, "Capacity of multiantenna Gaussian channels," *AT&T Bell Laboratories, Tech. Memo.,* June 1995.

[6] D. Gesbert et *al*, "From Theory to Practice: An Overview of MIMO Space-Time Coded Wireless Systems" *IEEE Journal Selected Areas in Communications,* Volume: 21 , Issue: 3 , April 2003 pp. 281 - 302

[7] G. Caire and S. Shamai, "On the achievable throughput of a multi-antenna Gaussian broadcast channel" *IEEE Trans. on Inform. Theory,* Vol. 49, No. 7, pp. 1691–1706, July 2003.

[8] H. Boche; A. Jorswieck and T. Haustein, "Channel Aware Scheduling for Multiple Antenna Multiple Access Channels" *Proc. 2003 The Thrity-Seventh Asilomar Conference,* Volume: 1 , Nov. 2003 pp. 992 - 996

[9] P. Viswanath; D. N. C. Tse and R. Laroia,"Opportunistic beamforming using dumb antennas," *IEEE Transactions on Information Theory*, Vol. 48, pp. 1277 -1294, June 2002.

[10] M. Sharif and B. Hassibi, "On the Capacity of MIMO Broadcast Channel with Partial Side Information," *submitted to IEEE Transactions on Information Theory*.

[11] P. Svedman, S. K. Wilson, L. Cimini, and B. Ottersten, "A simplified feedback and scheduling scheme for OFDM," *in Proc. IEEE Veh. Tech. Conf. (VTC 2004)*, Milan, Italy, May 2004.

[12] M. Sharif and B. Hassibi, "Scaling laws of sum rate using time-sharing, DPC, and beamforming for MIMO broadcast channels," *Proc. IEEE Int. Symp. Information Theory, Chicago*, Jun./Jul. 2004, p. 175.

[13] T. M. Cover, and J. A. Thomas, "Elements of Information Theory", John Wiley and Sons, New York, 1991.

[14] I. Toufik and M. Kountouris, " Power Allocation and Feedback Reduction for MIMO-OFDMA Opportunistic Beamforming," *IEEE VTC2006-Spring.* Melbourne, Australia 07-10 May 2006