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A Selective Cluster Index Scheduling Method in OFDMA

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Abstract—OFDM is an attractive solution for the design of future wireless communications due to its robustness to dispersion in multipath environments. Additional diversity gains can be realised by OFDMA by exploiting not only the temporal fading, but also spectral fading, that can result in higher rates due to increased diversity. A scheduler exploiting multiuser diversity imposes strict feedback requirements as channel quality information is required for every user's feedback unit with a feedback rate at least equal to the coherence time of the channel. The instantaneous signal to noise ratio is the most commonly used metric to quantify users' channel conditions. In OFDMA, the overhead due to feedback transmission increases significantly due to the fact that signal to noise ratio is required in the frequency domain, for every subcarrier of the OFDM symbol, which can potentially mitigate any multiuser diversity gains. This paper proposes a reduced feedback OFDMA design that requires very limited feedback information on a clustered subcarrier basis, whilst maintaining high downlink rates via Opportunistic Beamforming with multiple weighting vector transmission from the Base Station. This scheme is shown to be quite robust, as it can be easily adapted to variable channel conditions without any significant increase in complexity.

I. INTRODUCTION

Recent studies [1, 2] have shown that inherent temporal channel variations of a wireless link can be exploited in a multiuser environment, increasing the overall system throughput. By allowing only the user with the best channel conditions to occupy resources for every instant, the highest possible throughput gains can be realised. Higher spectral efficiency (bps/Hz) can be accomplished as the number of users in the cells increases, as the probability of identifying a very strong user for every time instant increases. In environments of low mobility and scatter, temporal fades are reduced in both number and amplitude, reducing the system's ability to exploit Multiuser Diversity (MUD). To overcome this problem, the idea of using multiple antennas at the Base Station (BS) to induce random channel fluctuations in slow fading environments has been proposed in [3]. It has been shown that implementing Opportunistic Beamforming (OB) in a slow fading scenario can achieve similar throughput gains for the same number of users as in an AWGN channel.

An efficient scheduler of OB entails severe feedback constraints as Signal to Noise Ratio (SNR) values are required to be fed back from all Mobile Stations (MSs) to the BS for every transmission instant. This configuration can result in a feedback overhead that can significantly hinder the overall link performance.

In recent years OFDM has emerged as a good candidate for PHY and multiple access for future wireless communications [4]. OFDM splits a high data rate stream into several lower rate orthogonal parallel streams. This approach is an attractive solution for the design of systems expected to operate in Non Line-of-Sight (NLOS) channels as it is tolerant to delay spread effects due to the longer symbol duration and the use of a Cyclic Prefix (CP).

Additional multiuser diversity gains can be extracted in OFDMA by jointly exploiting temporal and spectral variations of the channel, by scheduling different users on different frequency subcarriers of an OFDMA symbol. In [5, 6] it has been shown that the optimal power allocation in the frequency domain is achieved via waterfilling, where the allocated power to each subcarrier is adapted according to its instantaneous channel conditions. However, an equal power allocation approach can give similar performance to waterfilling [7], but has the added advantage of configuration simplicity. Also in [7] it was proven that the data rate of a multiuser OFDMA system is maximised by assigning one user per subcarrier.

In order for the BS to exploit MUD in the frequency domain, instantaneous SNR values for each of the subcarriers of each MS should be communicated to the BS. This requirement imposes additional feedback overheads, which depending on the number of generated subcarriers can impose substantial feedback overhead increases. For opportunistic scheduling, it is imperative that feedback should be provided at least at the rate at which the channel is changing, i.e. the coherence time. Hence for high vehicular speeds, the feedback rate considerably increases, where overall capacity eventually reaches bottleneck point after a certain speed. Several techniques for feedback reduction have been proposed [8-11], addressing the problem for a multiuser OFDMA system based on SNR feedback.

This paper presents an optimal configuration of a reduced feedback scheduling technique that does not rely on SNR feedback and thus can achieve significant feedback savings. Multiple Weighting vector Opportunistic Beamforming (MWOB) is employed to compensate for the lack of SNR information [12]. This approach is shown to be especially beneficial for a relatively low number of users.

This paper will show that the proposed scheme, not only maintains downlink rates at a much lower feedback overhead, but also, it can be easily reconfigured to meet changes in the channel coherence bandwidth. Throughput performance and feedback requirements are compared with other existing reduced feedback schemes.

II. SYSTEM PARAMETERS AND CHANNEL MODELS

The key parameters used in the simulations presented in this paper are listed in Table 1.

All simulation presented here have assumed a MISO configuration of a BS employing OB and equipped with 4 uncorrelated and independent transmit antennas and K single antenna Mobile Stations (MSs). A low rate error-free feedback channel is assumed for every MS. Full CSI is known at the MS end, but not at the BS. The ETSI BRAN channel model-A [13], of rms delay spread of $50ns$ is used. Simulations have been obtained for the other ETSI-BRAN models as well, to verify the initial statement of re-configurability of the proposed scheme to different channel environments. Due to space limitations however, these results are not presented in this paper. A uniform environment of an average SNR=0dB is assumed.

Table 1: System parameters

Operating Frequency	5 GHz
Bandwidth	100 MHz
FFT Size	1024
Transmit Antennas	4
Minislot length	5% of total downlink slot
Rms delay spread (τ_{rms})	50ns

III. FEEDBACK REDUCTION BY CLUSTERING AND SELECTIVE CLUSTER TRANSMISSION

The idea of grouping adjacent subcarriers into clusters and treating them as a single feedback unit [9], reduces feedback overhead by a considerable factor at the expense of minimal downlink throughput degradation. The extent to which adjacent subcarriers can be grouped together without substantial throughput degradation is dependent on their correlation, which itself is proportional to the coherence bandwidth of the channel, i.e. inversely proportional to the rms delay spread (τ_{rms}). The degree of correlation is also dependent on the subcarrier spacing [14]. For a specified τ_{rms} , a cluster size R that gives the best tradeoff between feedback overhead reduction and downlink throughput degradation exists. The optimum cluster size reduces as τ_{rms} increases, thus limiting the possibility of further feedback reduction. Provided N being the total number of subcarriers, the number of generated clusters is given by:

$$D = \frac{N}{R} \quad (1)$$

Given B is the number of bits required to quantise SNR values from each subcarrier, the feedback information in bits from each MS is therefore equal to DB . B is typically 5-6 bits in size but with coding can reach up to 30 bits [15].

A scheduler exploiting MUD does not schedule users on weak clusters. Hence, feedback information for these weak clusters of each MS may in fact convey redundant overhead, since these clusters have limited probability of being scheduled. In [9] it is proposed that each MS can in fact transmit SNR information regarding only the S strongest clusters for each symbol without major throughput losses, provided that the overall cluster outage probability stays low. The cluster outage probability is defined as the probability that none of the users have identified as eligible for transmission a given cluster. This configuration introduces however, the additional requirement of identifying these clusters, which can be done by transmitting the index of these clusters. A total feedback rate of $S[B + \log_2(D)]$ is thus required for each user.

Figure 1 (a) and (b) show throughput simulation results for a selective cluster scheme (with SNR based feedback) for a cluster size $R=32$ and $R=64$, respectively, for different numbers of fed back clusters. It can be seen that as the number of users in the system grows, this selective cluster scheme converges to the full feedback ($S=D$) scheme, due to cluster outage probability converging to zero. When the number of active users is small and/or the number of fed back clusters is small, significant throughput degradation is observed. This is

due to the fact that some clusters have not been selected by any of the users and remain unused.

The term spectral usage $\bar{U}$ is used in this paper to define the ratio of the number of allocated clusters U_k in a selective cluster scheme over the total number of available clusters D for a specified number of users K and corresponding fed back clusters S .

$$\bar{U} = \frac{U_k}{D} \quad (2)$$

U_k is defined as:

$$U_k = \left| \bigcup_{k=1}^K S_k \right| \quad (3)$$

S_k being the number of fed back clusters per user k , being equal for all users K .

Average spectral efficiency can be increased by increasing the spectral usage of the system. As a first step, the idea of reducing the number of available clusters D can be considered. By doubling the cluster size R , the number of available clusters D halves, allowing spectral usage to converge much faster to a full SNR scheme. For channel model-A, increasing the cluster size to $R=64$ gives only marginal throughput degradations compared to $R=32$, due to its relatively low rms delay spread.

Figure 1: Throughput of Selective Cluster Scheme (a) $R=32$, $D=32$, (b) $R=64$, $D=16$.

IV. SELECTIVE CLUSTER INDEX SCHEME

A. Conventional SCI with no provision for clusters in outage

In previous sections it has been argued that feeding back SNR values in an OFDMA scheme may not be a feasible solution, especially for high vehicular speeds, due to the large associated feedback overhead. This section describes how feedback overhead can be dramatically reduced by eliminating transmission of real valued SNRs completely in a selective cluster scheme.

A selective cluster scheme, where only the indices for the S strongest clusters are fed back to the BS is developed in this paper. This Selective Cluster Index (SCI) scheme reduces the total feedback rate from each MS to $S \log_2(D)$, eliminating the B parameter, which comprises the bulk of the feedback overhead. Initially a fixed S value for any given number of users will be assumed, resulting in a variable cluster outage probability.

The BS does not receive any SNR information from any of the MSs. The index of the selected clusters of each MSs can be considered as a form of non-deterministic feedback information, which does not give precise channel information, but provides an indication as to which clusters, each MS could be scheduled on. The BS treats the fed back cluster indices of all users with equal priority and resorts to random cluster allocation in the event where more than one MS is eligible for a given cluster. In [16] it was shown that the process of random MS allocation can preserve resource allocation fairness and also, depending on the degree of strong user identification process, achieve similar rate growth as a full feedback SNR scheme. The main challenge of the SCI scheme is to minimise the probability of several users being eligible in a cluster, whilst keeping cluster outage probability low. Figure 2 (a) presents throughput simulation results for the proposed SCI feedback scheme for a cluster size $R=32$ for different numbers of fed back cluster indices.

A direct tradeoff in throughput is observed for varying user numbers. For a relatively small number of users, feeding back a small number of cluster indices increases the probability of several clusters not being selected by any of the MSs, resulting in a decrease of the spectral usage. Increasing the number of fed back cluster indices for each MS reduces cluster outage; however, it results in poor selectivity for a high number of users, as the probability of more than one MS being eligible for a cluster increases. Due to the fact that the BS has only indicative channel quality information, it cannot distinguish between strong and weak users, resulting in random allocations. This effect can cause mitigation of MUD gains. This effect is evident in the scenario where each MS considers all clusters as eligible for transmission. In a fully SNR aware BS, this configuration results in maximum rate growth. However, in a SCI configuration, the scheduling algorithm would ultimately be reduced to a round robin configuration, where no MUD gains are extracted.

For a fixed S value the aim should be to determine a number of fed back clusters S that can result in a good trade-off between outage and strong selectivity over a range of users. For the numerical results of Figure 2 (a) the number of feedback cluster indices that gives the best tradeoff for a small and high number of users in terms of throughput performance is equal to $S = D/8$ for the user range assumed.

B. Increasing spectral fading via Multiple Weighting Vector transmission

In [12] it was shown that the transmission of multiple weighting vectors from the BS in an OB configuration can increase the temporal channel realisations for each MS, resulting in an increase of the diversity order, especially when the number of active users is small. As the number of users increases, inherent MUD becomes dominant and the MWOB scheme converges to the conventional OB, where only one weighting vector is transmitted. Transmitting multiple weighting vectors however imposes an overhead on the downlink time slot reducing the available time for useful transmission of data. Therefore, a constraint on their use should

be set. The optimum number of weighting vectors (Q_{opt}) that achieves the best tradeoff between diversity gains and downlink slot overhead can be computed for a given number of users and weighting vector overhead length as described in [12].

This paper adopts the use of multiple weighting vectors in an OFDMA system in order to increase fading in the frequency domain and alleviate reduction in downlink rates due to cluster index feedback, rather than SNR. In order to preserve correlation among subcarriers of the same cluster, multiple weighting vectors are transmitted over the cluster frequency range and the same precoding weights are used for all users. For each cluster the vector that gives the highest instantaneous channel gain is selected. Once the highest gains of each cluster have been selected, MSs transmit the index of the S strongest clusters in the same manner as with the conventional beamforming scenario but with the additional feedback requirement of transmitting the index of the best vector for each of the S clusters. The total feedback rate required for the SCI implementation with multiple weighting vector transmission is now $S \log_2 [D(Q_{opt} + 1)]$. Figure 2 (b) presents simulation results for the SCI scheme with multiple weighting vector transmission. Comparing results with those of the conventional OB with SCI it can be seen that spectral efficiency can be increased by up to 45%. Simulation results take into account the degradation of throughput due to the overhead associated with multiple weight transmission. Each vector occupies 5% of the total downlink slot and the optimum number of vectors for any number of users is used.

Figure 2: Throughput performance of SCI for $R=32$ (a) Conventional OB, (b) Multiple Weighting Vector OB

C. Random assignment of unallocated clusters

In Section A, it was been observed that the outage probability increases when the number of users is small, in conjunction with a small S value. An adaptive feedback scheme has been proposed in [11] where the number of fed back clusters for a given number of users K and clusters D is determined adaptively, so as to give an almost constant spectral usage. In an SNR based feedback scheme, maximum downlink rates are achieved for a spectral usage factor close to unity, i.e. minimising cluster outage to zero. This section describes an alternative method that guarantees full spectral usage in a SCI implementation with a constant feedback rate per MS.

For outage probability to be eliminated, and hence spectral usage to be increased, the number of feedback cluster indices

from each user has to be increased. However, it has been observed that a high S value reduces the ability of the BS to identify strong users. Some outage can therefore be beneficial in a SCI scheme in terms of increasing average downlink rates. Overall spectral usage can be increased by randomly allocating resources amongst all users for outage instants.

As the number of users increases, outage decreases (for a fixed S value). In order to quantify the extent to which in outage instants occur for specified K , D and S the mathematical approach in [11] has been adopted to theoretically determine the number of unassigned clusters $D - U_k$ using probability theory. Theoretical results have been compared and verified with simulation results. In Figure 3, theoretical and simulation results for $R=16$ and 32 are presented for different S values. The expected theoretical value of U_k is given by [9]:

$$E[U_k] = \sum_{u=S}^D u P_k(u - S) \quad (4)$$

where $P_k(i)$ denotes the i_{th} element of vector P_k containing the stacked, non-zero probabilities of the number of fed back cluster indices, when k users are active.

Figure 4 presents throughput simulation results SCI with MWOB with a cluster size $R=32$, for which clusters in outage are randomly assigned to users, from the entire group of K users. These results show that the number of fed back cluster indices that achieves the best tradeoff, for a small and high number of users now, becomes $S = D/16$ for the system under consideration. Comparing results of Figure 2 and Figure 4, the throughput improvement due to the increased spectral usage can be observed. Hence by randomly assigning unallocated clusters, in outage instants, not only downlink rate increases but feedback overhead reduces as well.

In [17] a reduced feedback OFDMA implementation with multiple vector transmission has been proposed. Under this scheme, each cluster compares the highest achievable channel gain (out of Q_{opt} different vectors) with a set predefined threshold levels. If the cluster has a gain higher than a threshold a non-zero sequence of bits, indicating eligibility for transmission and information regarding the selected vector, is transmitted. If not, a sequence of zeros is transmitted, indicating exclusion for transmission for the specific cluster. The total number of fed back bits per MS under this scheme is $D[\log_2(Z(Q_{opt} + 1))]$, where Z is the number of threshold levels used. The challenge of this scheme lies in finding the optimum threshold values that result in the highest user selectivity with minimum outage probability threshold levels need to be determined for different channel conditions. For the SCI implementation proposed here, only the correlation of adjacent subcarriers is used to determine an appropriate cluster size R and consequently an optimum S value. Additionally, the SCI implementation does not require information to be fed back for every cluster, but rather for only S clusters, reducing feedback overhead significantly. Figure 5 compares the feedback load overhead for an increasing cluster size for the two suggested schemes. It is assumed that unallocated clusters are randomly assigned to the active MSs and hence $S_{opt} = D/16$.

A single threshold level is assumed for the threshold design scheme. The optimum number of weighting vectors Q_{opt} is assumed to be four, a valid value for a range of 20-40 active users. As the cluster size increases, the SCI scheme gives a gradually decreasing feedback overhead, compared to the threshold design. Even for channel models with a high τ_{rms} a cluster size $R=16$ can be used, for which the SCI design requires almost 5 times less feedback information. The additional implementation simplicity associated with SCI makes it more practical and attractive approach towards reduced OFDMA opportunistic scheduling.

Figure 3: Theoretical and simulation results for unallocated clusters

Figure 4: SCI with Multiple weighting vector transmission (random assignment of unallocated clusters, $R=32$)

Figure 5: Feedback requirements for proposed OFDMA designs with multiple weighting vector transmission

D. Adaptive cluster request

Previous sections have assumed a fixed S value for the entire range of possible user numbers. This configuration results in a variable outage probability, which consequently gives a variable trade-off in downlink rate performance for different number of users.

In this section, an adaptive method for requesting fed back cluster indices which returns approximately a fixed P_{out} is used. Due to the discrete nature of S , an approximate value which most closely meets the target P_{out} is obtained. Depending on the number of available clusters, the accuracy for which fed back

clusters match the target P_{out} varies. Figure 6 shows the variation in the number of fed back clusters as a function of user number, for target P_{out} of 1% and 15% respectively, for a cluster size $R=32$.

As mentioned in earlier sections, the SCI can tolerate a certain degree of cluster outage, as this improves the strong user selectivity of the system in non outage instants. In Figure 7 the downlink performance of the SCI scheme using adaptive cluster selection is compared for target outages of 1% and 15%. A fixed $S=2$ curve is added for reference. Clusters in outage are randomly assigned. Results show that the SCI scheme performs better for a non-zero outage. An exhaustive simulation for a range of fed back clusters has indicated that a P_{out} value of about 15% achieves the best trade-off between strong user selectivity and outage. Hence, the SCI possesses the characteristic of increased throughput with reduced feedback overhead, which is the opposite of what is expected from an SNR based feedback scheme. Variations for the rate growth curves are attributed to the discrete nature of S . Additionally it can be observed that as the number of users increases the two fixed outage schemes begin to converge. This is due to the fact that cluster outage is bound by the number of users and no further adjustments to the S value can be made.

Figure 6: Adaptive S calculation for target outage probabilities

Figure 7: SCI throughput performance for adaptive cluster requests

V. CONCLUSIONS

This paper has considered the development of an optimal configuration of a scheduling algorithm for multiuser, OFDMA systems with Opportunistic Beamforming that promises major feedback overhead reductions by eliminating SNR feedback. It has also demonstrated how multiple weighting vectors can be applied in the frequency domain, as a means of alleviating losses in MUD arising from the lack of SNRs at the BS. Two approaches in determining an appropriate number of fed-back cluster indices were discussed.

A fixed S value results in variable cluster outage probability. A tradeoff in performance for a variable user numbers has been observed. An adaptive calculation of fed

back indices, as a function of the number of users preserves a near constant outage probability. Exhaustive simulations (not presented here due to lack of space) have quantified the cluster outage probability for which the best tradeoff between strong user identification and outage minimisation. The proposed selective cluster index scheme, not only improves downlink rate performance by tolerating a certain outage, but also manages to minimise feedback overhead even further.

This scheme can be particularly beneficial for MSs travelling at vehicular speeds, for which the channel coherence time is small and feedback rate is high. Due to the increased intolerance to feedback overhead, the proposed SCI scheme has the ability to maintain MUD gains at much higher speeds, than an SNR based feedback scheme.

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