



Nicolaou, M., Doufexi, A., Armour, SMD., & Sun, Y. (2011). Reduced feedback selective cluster index scheduling with user pre-selection for next-generation multi-input multi-output orthogonal frequency division multiple access system. *IET Communications*, 5(6), 853 - 863.  
<https://doi.org/10.1049/iet-com.2009.0804>

Peer reviewed version

Link to published version (if available):  
[10.1049/iet-com.2009.0804](https://doi.org/10.1049/iet-com.2009.0804)

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# Reduced feedback selective cluster index scheduling with user pre-selection for next generation MIMO-OFDMA systems

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## Abstract

The joint use of Opportunistic scheduling and Orthogonal Frequency Division Multiple Access (OFDMA) provide significant diversity gains even in environments of low mobility and scatter for which channel variations are low. The downside of opportunistic scheduling, in multicarrier systems such as OFDMA, lies in the substantial uplink overhead required to be fed back by the Mobile Stations (MSs) describing users' instantaneous link conditions. This paper presents a novel approach towards multicarrier opportunistic scheduling for a MIMO configuration that promises major uplink feedback overhead reductions with only minor degradations on downlink throughput performance. The conventional channel quality indicator (CQI), in the form of instantaneous Signal to Noise Ratio (SNR) is replaced by an alternative metric, in the form of the index of the strongest frequency clusters of each MS, which imposes a significantly reduced overhead.

This paper examines the performance of the proposed channel quality metric for Random Beamforming and examines the benefits in terms of throughput and feedback overhead over existing schemes. Results show that the proposed scheduling approach maintains performance within 1dB of a full SNR feedback scheme whilst achieving a reduction of the required uplink feedback overhead by a factor of up to 24 and also providing improved fairness amongst users experiencing different channel gain levels.

Index Terms –Multiuser Diversity, Channel Quality Information, Scheduling

## I. INTRODUCTION

OFDMA has emerged as one of the most promising PHY and multiple access candidates for future wireless communication systems [1], as indicated by its adoption for the physical layers of IEEE 802.16 and the Third Generation Partnership Project (3GPP) Long Term Evolution (LTE, downlink only). This is due to the resilience of OFDM to delay spread and the capability for simultaneous transmissions across different frequency channels for multiple access purposes.

Opportunistic scheduling schemes improve the capacity of wireless systems by dynamically scheduling users according to their instantaneous channel strength [2, 3]. The Multiuser Diversity (MUD) principle suggests that the probability of identifying a user with strong instantaneous conditions for every scheduling slot is proportional to the number of active users. Additional MUD gains can be extracted in OFDMA by exploiting spectral as well as temporal fading [4, 5]. The combined use of OFDMA and opportunistic scheduling considerably increases the uplink (UL) feedback load, since the number of resources for which feedback is conveyed is increased. In order to efficiently exploit MUD, timely and accurate channel information from individual MSs must be conveyed to the Base Station (BS) where resource allocation decisions are made. In IEEE.802.16e, the UL CQI feedback information consists of one bit of hybrid-automatic-repeat-request (HARQ) and five bits of quantised SNR values. Additional coding can increase the feedback overhead up to 30 bits [6]. In [7] it was shown that the conventional notion of obtaining CQI values for all users' channels is quite inefficient, as it consumes a significant portion of the available UL bandwidth. Recent work [8-11] has concentrated on ways of reducing this load, while minimising the impact of reduced UL information on the DL throughput. More specifically, several ideas aimed at reducing feedback for multiuser OFDMA scheme have been developed in [12-15].

The rate at which the feedback mechanism is activated should correspond to the fading rate of the channel. CDMA High-data-rate (HDR) systems require feedback from MSs twice in a 1.667ms slot [16]. High Speed Downlink Packet Access (HSDPA) defines a set of possible feedback intervals that provide a greater flexibility in reducing UL network traffic under slow fading environments [6]. The channel coherence time of the 802.16-Stanford University Interim (SUI) channel model can be matched to a corresponding MS velocity. The feedback reporting mechanism rate as a function of this velocity has been presented in [17]. In [18] the effect of SNR quantisation was examined, showing that a high accuracy can be preserved with a relatively small number of quantization levels via a logarithmic threshold setting.

A great challenge lies in reducing UL feedback requirements, with a minimum impact on DL capacity. This paper introduces a new CQI metric that provides only indicative information regarding instantaneous channel conditions of users that does not rely on quantised SNR values to accomplish MUD gains. This indicative information is comprised of

only the index of the preferential frequency resources across an OFDM symbol for each user, which imposes a considerably lower overhead. Due to the nature of the proposed CQI, conventional opportunistic scheduling algorithms that rely on SNR information at the BS cannot be employed. Alternative resource allocation and scheduling techniques that incorporate the proposed metric are proposed and examined in this paper. A user pre-selection stage [19] that limits the number of users participating in the resource allocation procedure is also considered in this paper, as an initial step towards achieving feedback reduction. The adoption of user pre-selection in combination with the proposed CQI metric provides enhanced user selectivity, allowing for improvements in DL throughput for the proposed channel quality metric. Contrary to the conventional notion of feedback (whereby more information allows for better exploitation of the channel resources), analysis of the proposed metric shows that performance improvements arise from the diminution of feedback information. Since the proposed metric provides only relative channel strength indication, this reduction in feedback allows for better selectivity, since non-preselected users are restricted from transmitting channel information for scheduling purposes. The proposed approach shows considerable uplink feedback savings over SNR based feedback schemes, as well as other existing reduced feedback schemes that do not rely on SNR feedback [8, 20], since it allows for feedback savings via a reduction of the CQI size as well as reduction of the number of resources for which CQI is required.

This paper focuses on a 2x2 MIMO, spatial multiplexing, Random Beamforming scheme. However, the proposed implementation holds for MISO Opportunistic Beamforming as well as schemes exploiting the spatial dimension for resource allocation (e.g. Layered Random Beamforming, Multiuser-MIMO etc).

## II. PERFORMANCE BENEFITS FROM MULTIUSER DIVERSITY VIA OPPORTUNISTIC AND RANDOM BEAMFORMING

### *A. Opportunistic Beamforming*

The MUD technique proposed in [2] suggests that temporal channel fading can be exploited by scheduling a user whose instantaneous channel gain is near its peak for every transmission instant. Maximum MUD exploitation occurs under environments of high scatter. When these conditions do not exist, the Opportunistic Beamforming (OB) strategy [21] can increase the dynamic range of amplitude allowing for the full benefits of MUD to be exploited. According to Shannon's capacity theorem [22], the requested sum rate of a user  $k$  is given by:

$$R_k [t] = W \log_2 \left( 1 + \frac{P_k |H_k(t)|^2}{N_0} \right) \quad (1)$$

where  $W$  indicates the total system bandwidth,  $P_k$  the associated assigned power to a user  $k$ ,  $H_k(t)$  indicates the instantaneous channel gain of user  $k$  at instant  $t$  and  $N_0$  is the noise level. Equal power allocation is assumed in this study. A study whereby multiple precoding vectors are employed to increase diversity gains when diversity is inherently limited by the number of users has been considered in [23].

### B. Spatial Multiuser Diversity with Random Beamforming

Random Beamforming (RB) [26] is a technique that uses Singular Value Decomposition (SVD) and is capable of achieving spatial MUD gain and spatial multiplexing gain. The extension of RB to an OFDMA scenario [27] can provide spatial multiplexing capacity gain as well as spatial and spectral multi-user diversity gain. A unitary matrix  $V_r$  is generated from a random channel matrix  $H_r$  and is applied to the subcarriers of the OFDM symbol on a sub-channel basis. The received signal after the FFT and guard interval removal becomes:

$$\begin{aligned} Y_k^s &= H_k^s V_r^s X_t^s + N_k^s \\ &= U_k^s D_k^s (V_k^s)^H V_r^s X_t^s + N_k^s \end{aligned} \quad (2)$$

where a subscript  $k$  denotes a MS index,  $s$  denotes a subcarrier index,  $H_k^s$  being a matrix containing the frequency responses of the channels between  $N_t$  transmit and  $N_r$  receive antennas for subcarrier or a cluster. A cluster in an OFDMA system is defined as a group of adjacent consecutive subcarriers treated as a single feedback and resource unit and the number of subcarriers per cluster is defined as the cluster size [28].  $D_k$  is the diagonal matrix including all singular values of  $H_k^s$ ,  $U_k^s$  and  $D_k^s$  are the unitary matrices obtained by applying SVD to  $H_k^s$ .  $X_t^s$  denotes an  $N_t \times 1$  matrix containing the transmit signals at subcarrier  $s$  at the BS and  $N$  represents the additive complex Gaussian noise. A pseudo-random beamforming approach has been proposed for LTE [29, 30], for which transmitted data are pre-coded using a known codebook of unitary matrices, generated on a Fourier basis.

For a 2x2 MIMO system, the MIMO channel can support up to 2 data streams transmitted over 2 parallel sub-channels. For data stream  $q$  at every sub-carrier, the MS  $k$  computes the Effective SNR (ESNR) which indicates the channel quality (for simplicity, the subcarrier index is omitted):

$$ESNR_k^q = \frac{|D_k|_{qq}^2 |(V_k^H V_r)_{qq}|^2 E_s}{|D_k|_{qq}^2 |(V_k^H V_r)_{qj, q \neq j}|^2 E_s + N} \quad (3)$$

Providing ESNR feedback on every physical resource block may not be feasible in practice due to the increased associated UL feedback overhead. Alternative methods of ensuring efficient exploitation of MUD with reduced UL overhead need to be considered. Subsequent sections develop numerical and analytic results for a 2x2 RB-OFDMA spatial multiplexing scheme, due to the apparent benefits of spatial multiplexing that this implementation offers. It

should be noted however, that analysis based on the proposed metric is readily extendible to higher order MIMO schemes as well, as will be discussed in subsequent sections.

### III. REDUCED FEEDBACK ALGORITHMS

This section initially describes two existing partial feedback strategies that adopt the quantised ESNR metric for CQI representation. These techniques are modified and incorporated in the scheduling process according to the proposed channel quality metric and the corresponding resource allocation strategy that relies on information regarding only the eligibility of users in a cluster.

#### A. Best- $M$ User Pre- Selection

The scheme proposed in [32] identifies the strongest users in the temporal dimension by averaging channel gains across the frequency domain. The best- $M$  user subset is determined based on the corresponding average SNR values. The BS broadcasts this list of eligible users back to the MSs. This DL overhead is considered negligible. Assuming  $K$  users in total, the total UL CQI feedback load for scheduling purposes expressed in terms of bits is:

$$FB = B(K + M.D) \quad (4)$$

Where  $D$  is the number of available clusters and  $B$  is the number of bits for representing the quantised ESNR value.

This scheme can result in some loss in throughput due to degradations in MUD by failing to exploit peak channel conditions from non-selected MSs.

#### B. Selective Cluster Feedback

An opportunistic scheduler rarely schedules users on their weak clusters. Hence, ESNR information for such clusters can be redundant [15]. The amount of UL feedback can therefore be reduced by restricting users to feed back ESNR values for only their  $S$  strongest clusters. The  $S$  parameter can be chosen such that the probability of information outage resource is kept to a minimum, in order to avoid excessive blind resource allocation instances. Figure 1 (a), highlights this argument by considering a selective cluster scheme under different number of fed back clusters. A notable degradation in throughput, observed for a combination of small  $S$  values and small number of users, is attributed to the increased resulting scheduling outage which gives rise to more frequent instances where suboptimal resource allocation strategies (e.g. Round Robin, Blind Assignment) are employed. An adaptive method of calculating  $S$ , for maintaining a near constant cluster outage as developed in [15], is adopted here for examining system performance under the proposed channel metric under different parameters.

Selective cluster schemes introduce the additional requirement of feeding back information regarding the indices of the  $S$  selected clusters. The amount of feedback overhead for CQI on the spectral resources per user in terms of bits for the selective cluster feedback scheme is calculated by:

$$FB = S(B + \log_2(D)) \quad (5)$$

### C. Selective Cluster Index Feedback

This section describes the proposed metric that dramatically reduces feedback overhead by eliminating transmission of real valued ESNRs, by introducing a metric that provides only relative indication of channel strength, resulting in a considerably reduced CQI size, in conjunction with a selective cluster scheme.

A variation of the selective cluster scheme [33], where only the indices of the  $S$  strongest clusters of each MS are fed back to the BS is proposed here as an alternative to ESNR based feedback. This scheme, henceforth referred to as ‘Selective Cluster Index’ (SCI), reduces the feedback for the spectral dimensions to  $S \log_2(D)$ . The index of the selected clusters for each MS provides no precise information on channel strength, but can be treated as an indication of the clusters of each MS, for which assignment on these resources would best exploit spectral variations in an opportunistic manner. The BS treats MSs classified as eligible in a given cluster with equal priority and resorts to a random allocation in the event where more than one MS is eligible. This random allocation is a direct consequence of the lack of explicit ESNRs at the scheduler. The main challenge of the SCI scheme lies in improving the strong user identification process, by minimising the probability of identifying multiple users as eligible in a cluster, whilst simultaneously keeping cluster outage probability low.

Figure 1 (b) presents numerical throughput results for the proposed SCI feedback scheme for the same parameters as in Figure 1 (a). For outage instants, clusters are randomly assigned amongst all active users with equal probability. For a combination of small number of users and fed back cluster indices, the cluster outage probability increases, deteriorating spectral efficiency, due to increased instances where completely blind resource assignments take place. However, increasing the number of fed back cluster indices from each MS combined with a large number of users results in poor selectivity. Due to the fact that the BS is only equipped with relative channel information, no distinction between strong and weak users can be made and hence MUD gains are compromised. In an ESNR based feedback scheme, feeding back all clusters results in maximum rate growth. For SCI based scheduling, resource allocation is reduced to a completely random assignments when all clusters are fed back, as highlighted by the curve where  $S$  is set to the total number of available clusters in Figure 1 (b).

#### IV. USER PRE-SELECTION WITH SELECTIVE CLUSTER INDEX RESOURCE ALLOCATION

##### A. Resource Allocation Algorithm

Figure 2 illustrates the procedure of the proposed scheduling method as follows:

**Step 1:** The BS transmits a precoding matrix to the MSs, requesting average ESNRs from each MS

**Step 2:** Each MS determines the average ESNR across the entire frequency domain and feeds it back to the BS.

**Step 3:** The BS selects the best- $M$  users out of a total of  $K$  users based on the received CQI.

**Step 4:** The BS broadcasts the list of eligible users and requests cluster eligibility information for the eligible users for their  $S$  strongest clusters.

**Step 5:** For each cluster, the BS identifies the subset of eligible users ( $m_f$ ). If a cluster is not in outage, the BS randomly assigns a user from the  $m_f$  subspace, otherwise, a user  $k$  out of all  $K$  users is selected.

It should be noted that this procedure is directly applicable and analysis is consistent to a Layered Random Beamforming (LRB) as well, which provides an extra degree of freedom in the spatial domain. SCI feedback would be required on a spatial layer basis identifying eligible users on each layer independently. Diversity benefits arising from the direct exploitation of the spatial domain [28] are expected to be reflected on the SCI scheduling approach. The SCI scheme can be generalised to any  $N_T \times N_R$  MIMO spatial multiplexing scheme, with cluster outage analysis consistent on each of the  $\min(N_T, N_R)$  available spatial layers independently.

##### B. Cluster Outage Probability Analysis

Cluster outage is defined as the event where no users have indicated eligibility for a cluster ( $n$ ). The outage probability ( $P_{\text{out}}$ ) is expected to increase for a fixed  $S$  value, as the number of pre-selected users decreases. When a cluster is in outage, the scheduler resorts to a completely blind resource allocation. This randomness causes considerable throughput degradation due to a lack of MUD exploitation.

It is assumed that each user feeds back indices about a subset,  $S_k$ , of the total number of available clusters  $D$ , with  $|S_k| = S$ . The random variable  $U_k$  denotes the number of different clusters, out of  $D$  clusters, that have been indicated as eligible when  $k$  users have made their pick, i.e.

$$U_k = \left| \bigcup_{i=1}^k S_k \right| \quad (6)$$

Based on the analysis in [34] the number of unallocated clusters in a selective cluster feedback scheme can be computed as

$$U_k = \sum_{u=S}^D u P_k(u-S) \quad (7)$$

where  $P_k(i)$  denotes the  $i$ -th element of  $P_k$ , where  $P_k$  is the array of the non-zero outage probabilities as a function of  $S$  when  $k$  users are present in the system.

The cluster outage probability  $P_{out}$  can be expressed as a joint function of the best- $M$  pre-selected user subset and the corresponding fed back cluster indices ( $S$ ), i.e.  $P_{out}(M, S)$ . Two resource allocation policies are employed depending on the condition of outage. If the cluster is not in outage the BS selects a user from the  $m_f$  user subspace, otherwise it selects a user for the entire set of  $K$  users. Figure 3 (a) shows the expected outage probability for a user pre-selection scheme employing selective cluster feedback, as a function of fed back users and fed back clusters. The expected number of clusters not in outage is given by  $F = D(1 - P_{out})$ , which is also equal to  $F = \left| \bigcup_{i=1}^M S_i \right|$ . The number of clusters in outage is therefore given by  $E = DP_{out}$  which is also equal to  $E = D - F$ .

The main challenge of the best- $M$ /SCI implementation lies in keeping the  $m_f$  subspace close to unity in order to improve efficient strong user selection, while simultaneously preserving a low average  $P_{out}$ . These two targets are however contradictory and should therefore be chosen to achieve the best trade-off. Reducing the number of eligible users per cluster ( $m_f$ ) for a fixed best- $M$  value is achieved by increasing the target outage probability, i.e. reducing the number of fed back cluster indices, which consequently give rise to increased outage instants. For a selective cluster scheme employing user pre-selection, the  $S$  parameter can be adaptively determined for a given number of pre-selected users such that an approximately constant  $P_{out}$  is maintained. Figure 3 (b) shows the variations in the calculated  $S$  value for a range of different best- $M$  values for target outage probabilities set at 1, 10 and 20%, for a cluster size  $R=32$ . It can be observed that  $S$  remains constant over a range of pre-selected users, which is attributed to the granularity of  $S$ , leading to deviations in the actual outage to the target  $P_{out}$ .

## V. PERFORMANCE ANALYSIS FOR RANDOM BEAMFORMING

In order to evaluate the proposed best- $M$ /SCI scheme scheduling for RB-OFDMA, simulation results under different target outage probabilities have been obtained and compared with a full ESNR based feedback scheme. The key simulation parameters of the proposed reduced feedback OFDMA schemes are listed in Table 1. The ETSI/BRAN channel Models  $A$  and  $E$  [31], with corresponding rms delay spreads ( $\tau_{rms}$ ) of  $50ns$  and  $250ns$  are used, allowing for a performance comparison under normalised delay spreads of 0.5 and 2.5 respectively for a 10Mbps transmission rate. A low rate error free feedback channel is available to every MS. Full Channel State Information (CSI) is available at the

MSs but not at the BS. All users experience independent channel fading, normalised for an average SNR=0dB, unless explicitly stated otherwise. Instantaneous channel gains can deviate significantly from the mean even in the normalised channel scenario.

#### *A .Spectral Efficiency Results*

The system throughput is comprised of the sum of the DL bit-rates of all MSs. In Figure 4 (a), the average spectral efficiency for different numbers of pre-selected users is compared for a set of different target outage probabilities (1, 10, 20 %) for a cluster size  $R=32$ . The total number of users  $K$  is set to 50, the number of best- $M$  pre-selected users ranging from 5 to 50. A fluctuation in throughput can be observed as the number of pre-selected users varies for a specified target outage. This fluctuation is attributed to the inability of the system to maintain a constant cluster outage for different numbers of pre-selected users. Two conflicting effects are the cause for these fluctuations.

Comparing the curve for a 10% target outage, a reduction in throughput is observed when moving from  $M=25$  to  $M=30$ . Over this range of pre-selected users, the outage probability drops well below the target  $P_{\text{out}}$ . Consequently, an increase in the number eligible of users per cluster ( $m_f$ ) is expected, which reduces the effectiveness of the BS to identify one of the strongest users. A performance degradation is also observed for a target  $P_{\text{out}}$  of 20% when moving from  $M=25$  to  $M=30$ . This degradation is more severe than for a 10% target outage. This phenomenon is attributed to the fact that the actual outage is much higher than the target one. As a consequence, the BS resorts more often to completely random allocations, assigning resources amongst  $K$  users rather than from a smaller  $m_f$  user subspace. One way to avoid excessive cluster outage is to cap the cluster outage probability to a maximum value, rather than allowing it to fluctuate around it. However, this approach can lead to considerably lower actual outage occurrences for some best- $M$  values, which can degrade performance due to poor selectivity at the BS.

Results indicate that tolerating a certain percentage of cluster outage can in fact improve spectral efficiency, as it provides an improved compromise in keeping the  $m_f$  user subspace small in non-outage events, whilst preserving cluster outage occurrences at an acceptable level. This result is in direct contrast to conventional ESNR feedback based schemes, where outage should be kept to a minimum for rate maximisation. The proposed scheduling approach for the SCI scheme is based upon a “*less is best*” approach regarding the feedback of channel quality parameters, achieving not only improvements in DL spectral efficiency, but also providing UL feedback overhead savings. Another result that can be inferred from this restrained transmission of feedback parameters is that higher spectral efficiency is achieved via the pre-selection stage, which restricts access to resources to users that tend to under-utilise resource in the long-term. Unlike the user pre-selection scheme considered in [32] based on ESNR based feedback, a best- $M$  user pre-selection

method can result in improved link capacity when compared to a scheme not incorporating the user pre-selection stage for the proposed SCI scheduling scheme.

### B. Exhaustive Search of Optimum Parameters

In order to determine the optimum number of fed back cluster indices for which throughput is maximised, an exhaustive search over a range of possible  $S$  values and corresponding best- $M$  subsets is considered in this section. Different delay spreads and different cluster sizes have also been investigated, for which an optimum set of parameters can be identified in the same manner. Figure 4 (b) **Error! Reference source not found.** shows the resulting spectral efficiency values for a range of possible  $S$  and best- $M$  values, for channel Model  $A$  ( $\tau_{rms}=50\text{ns}$ ) for a cluster size  $R=8$ . The rather smooth curvature is attributed to the wide range of available  $S$  values. A larger cluster size would impose a higher limitation on the number of available clusters, which would result in a rougher curvature of the exhaustive search plane.

A look up table with optimum  $S$  values for a specified range of pre-selected users and cluster sizes can be generated. Table 2 considers optimum  $S$  values for a cluster size  $R=16$ , for the ETSI/BRAN channel Models  $A$  and  $E$ . The optimum  $S$  value does not vary significantly over a wide range of delay spreads, allowing the same set of parameters to be used over a large range of varying channel conditions. Based on the findings of Figure 4 (b), it can be deduced that an optimum throughput performance as a function of the best- $M$  admitted users requires a cluster outage in the region of 10-20%. Therefore, the expected optimum performance for SCI would ride the peaks of the curves of the considered outage probability scenarios outlined in Figure 4 (a).

### C. Feedback overhead implications

The combined use of the SCI metric with user pre-selection can provide added uplink feedback savings, as shown by Figure 5 (a), by reducing the number of pre-selected users and restricting the number of clusters onto which these users could be scheduled. The SCI resource allocation policy results in higher throughput performance by tolerating some degree of outage, as this can improve the strong user identification process. Figure 5 (b) presents the feedback load for CQI transmission in terms of bits for RB-OFDMA for a cluster size  $R=32$ , using the SCI scheduling metric, plotted as a function of the best- $M$  user values for target cluster outage probabilities of  $P_{out} = 1, 10, 20\%$ . Due to the adaptive calculation of  $S$  adopted for attaining a specified target outage, the system does not necessarily return a lower feedback overhead for smaller best- $M$  values. Hence, the selection of an appropriate best- $M$  value requires not only DL rate considerations, but the decision may also incorporate UL feedback overhead considerations. The optimum throughput performance, obtained via exhaustive search, as a joint function of the optimum feedback parameters and the corresponding feedback load is presented in Figure 6. The UL feedback overhead for CQI transmission corresponding to

a best- $M$  value of 25 is equal to 500 bits per OFDM symbol. With the conservative assumption of  $B=5$  the feedback load would accumulate to 8000 bits per symbol. This example of a 16-fold reduction in feedback requirement demonstrates the powerful capabilities of the best- $M$ /SCI feedback scheme in reducing the UL feedback requirements.

In [9], the idea of exploiting MUD, via a 1-bit feedback information was proposed. Work in [20] has extended this concept, showing that considerable throughput benefits can be achieved via the combined use of multiple precoding and multiple threshold design which allows for a more efficient identification of strong users. The increase in uplink feedback overhead with respect to the original 1-bit feedback scheme has been justified by an improvement in the aggregate downlink throughput. Threshold based feedback schemes achieve overhead reduction by reducing the size of the CQI metric. However, the SCI scheme attains further overhead reductions by not only reducing the size of the CQI, but by also reducing the number of resources for which feedback is conveyed. Figure 7 (a) shows the ratio of the feedback load of each of the referenced schemes over the load of the SCI scheme with optimum parameter selection, for varying cluster sizes. The SCI scheme is considerably more efficient in terms of uplink overhead with regards to the referenced schemes. For an increasing cluster size the benefits of the SCI scheme are even higher, due to the reduction in both the number of feedback cluster indices  $S$ , as well as in the size of the index,  $\log_2(D)$ . Beyond a certain cluster size however,  $S_{opt}$  inevitably converges to unity, limiting the ability of the SCI scheme to achieve linear reductions in feedback. Nevertheless, even under such conditions, the proposed scheduling algorithm attains a 3-fold feedback saving from the least spectrally efficient, 1-bit per resource feedback approach, and up to a 7-fold increase over the more spectrally efficient multiple precoding scheme ( $Q=3$ ) based on a two-threshold implementation [20]. The spectral efficiency for the SCI and the referenced threshold based schemes for  $K=50$  is compared in Figure 7 (b). It can be seen that the SCI performs very closely to the most spectrally efficient threshold assisted scheme, despite the considerably reduced associated feedback overhead.

#### *D. Fairness Under non-uniform channel distributions*

The performance analysis of the SCI feedback scheme has so far concentrated on throughput and feedback overhead, on the assumption of a uniform channel distribution across all users. In real scenarios, different users can experience different path losses. The adoption of user pre-selection can enable the scheduler to identify the subset of users experiencing considerably lower path losses and perform scheduling on this subset only. However, in practice, such an implementation would result in a considerably unfair resource allocation, for which users experiencing more severe path signal degradations will be deprived of resources, leading to a failure in meeting their respective Quality of Service (QoS) requirements. By considering all users as eligible, SCI based scheduling can provide increased fairness, since eligible users in a given cluster have equal probability of resource assignment. Long term throughput fairness has been

conventionally achieved via the Proportional Fair (PF) scheduling algorithm [21]. Depending on the variability of channel conditions across different users, convergence of the PF algorithm to a completely fair throughput allocation may exceed the maximum packet delay constraints of particular applications, leading to a failure in delivering timely service, a problem especially evident in real-time applications [35]. To highlight the associated fairness of SCI scheduling, the Jain's Fairness index ( $J$ ), defined in equation (8), is calculated based on a non-uniform channel gain environment, where users are randomly scattered in a cell, with BS-MS distances varying from 200m to 1000m. Path loss is calculated based on the COST Walfish-Ikegami-Model (COST-WI) [36]. The transmit antenna power is set at 43dBm.

$$J = \frac{\left| \sum_{i=1}^n x_i \right|^2}{n \sum_{i=1}^n x_i^2} \quad (8)$$

The associated sum rate performance  $\sum_k R_k$  and the corresponding Jain's Fairness index ( $J$ ), for a max. SNR algorithm, PF with window lengths  $T_c=10, 1000$ , SCI scheduling and a Round Robin approach for a total number of users  $K=50$  approach is presented in Table 3. The max. SNR algorithm attains the highest throughput, at the expense of high unfairness, since resource allocation is dominated by the few users experiencing low path losses. A small window length for the PF algorithm, which shifts the weighting of the selection metric towards the average throughput utilisation, thus increasing fairness, manages to achieve only a modest improvement in fairness due to highly unequal channel gain distributions. The SCI approach achieves significantly higher fairness, due to the equal priority assigned to eligible users. A Round Robin approach, which does not incorporate any MUD exploitation, achieves similar fairness levels with SCI scheduling, attaining however considerably lower throughput. It can therefore be deduced that under highly diverse channel conditions, the adoption of the cluster index as the CQI metric of choice can provide improved fairness, potentially allowing QoS targets for real-time applications to be met, without severe degradations in the aggregate throughput performance of the system. In order to verify numerical analysis of the best-M/SCI scheduling algorithm in RB-OFDMA, Bit Error Rate (BER) results for a total number 50 MSs for channel Model  $A$  are presented in Figure 8. For reference, a round robin scheduling algorithm which does not require any feedback, is included. 64QAM modulation and  $3/4$  coding rate is considered; results are however consistent for any modulation and coding rate combination. A full ESNR based feedback scheme is shown to achieve the best performance, due to full MUD exploitation. However, a best-M/SCI implementation, with optimum feedback parameters, results in only 1dB degradation with respect to the ESNR based feedback scheme and in a very similar performance to the threshold assisted feedback scheme with multiple precoding, as indicated by numerical results in Figure 7 (b). Performance degradation is attributed to the certain degree

of randomness in the resource allocation, that can result in scheduling some users in poor channel instances, resulting in excessive errors. A SCI approach that considers all users as eligible for resource allocation is marginally worse than the best- $M$ /SCI combination, due to the greater extent of random allocations and consequently the loss of multiuser diversity gains.

These results are consistent with the numerical analysis which shows that a best- $M$ /SCI scheduling policy in a uniform channel scenario can return higher throughput than a SCI scheme that considers all users as eligible for resource allocation. The optimum best- $M$  user value is dependent on the number of available clusters. Provided that the number of users requiring service is moderately large, the optimum number of fed back users does not change. Also, as has been shown in previous sections, the optimum parameters do not deviate substantially as a function of the rms delay spread. This result is particularly important as it facilitates the configurability of a system that employs such a metric under diverse channel conditions, eliminating the need for cumbersome exhaustive searches of optimum parameters for different environments.

## VII. CONCLUSIONS

Uplink feedback overhead for multicarrier systems exploiting multiuser diversity is a major design issue, that can significantly hinder the performance of a wireless system. Traditionally, channel quality information in the form of instantaneous quantised ESNR values has been used to exploit the fading nature of wireless channels. However, in high mobility environments, where channel quality information needs to be provided at a much higher rate, the associated uplink overhead becomes excessive, resulting in a bottleneck in the performance of the wireless link.

A new channel quality metric for multicarrier systems that requires significantly less overhead than the conventional approach has been proposed in this paper and tested under a MIMO-OFDMA, Random Beamforming scenario. The proposed implementation achieves major uplink overhead reductions by replacing the ESNR metric with a relative indicator of channel strength, in the form of the index of the best spectral resources for each user.

Due to the lack of explicit ESNR values, a resource allocation strategy whereby the Base Station makes decisions based only on this relative channel quality information has been proposed. The performance of a Selective Cluster Index scheme improves through the adoption of an initial user pre-selection stage, which excludes users that are likely to under-utilise the channel resources from the scheduling process. The user pre-selection stage not only manages to improve the efficiency of the resource allocation process but can also reduce uplink feedback overhead even further.

Two important parameters affecting the performance of a system adopting the proposed selective cluster index quality metric have been identified. These are the cluster outage probability and the number of users declaring cluster eligibility in non-outage events. This paper has demonstrated that these parameters are interrelated. A trade-off between

these parameters has been identified for channel scenarios under different parameters, such as cluster size and delay spread, through an exhaustive simulation over a range of possible parameters values.

Results have shown that, unlike conventional feedback schemes that rely on ESNR information, a certain cluster outage for the user pre-selection SCI scheme can be tolerated, as it can in fact increase downlink rates, since strong user selectivity at the BS is increased, improving the efficiency of the resource allocation process. Cluster outage levels for which maximum throughput performance is achieved were shown to lie in the region of 10-20% for a uniform channel environment. Outage probability is inversely proportional to the amount of feedback information. A system that can tolerate a degree of outage achieves reduction in feedback overhead, which is the main scope of this paper. The associated fairness of the proposed metric has been tested under a channel scenario where different users experience highly different path losses. The SCI scheduling approach has shown to achieve a much better trade-off between throughput performance and fairness compared to a Proportional Fair scheduler and a Round Robin approach.

The performance of the resource allocation process under the proposed cluster index metric has been examined under different parameters. A smaller cluster size has shown to be more accurate in terms of preserving a target outage probability, albeit at the expense of increased feedback overhead. Substantial reductions in uplink feedback requirements can be achieved at the expense of moderate reductions in downlink throughput. Physical layer simulations show that the proposed scheme can achieve a BER performance very close to that of a full ESNR feedback scheme. This property, along with the added benefits of reduced feedback overhead and improved fairness, proves to be a good solution for providing service for users at wide range of speeds, due to the enhanced immunity to higher associated feedback overheads. Conventional schemes employing ESNR feedback can reach a bottleneck point when the uplink feedback rate is high. Hence, we propose that the SCI resource allocation approach with user pre-selection can provide a good solution towards providing service in fast fading environments with minimum impact on the aggregate system performance.

#### ACKNOWLEDGMENTS

The authors wish to acknowledge the financial support of Toshiba Research Europe Limited (TREL) and the Engineering and Physical Sciences Research Council (EPSRC).

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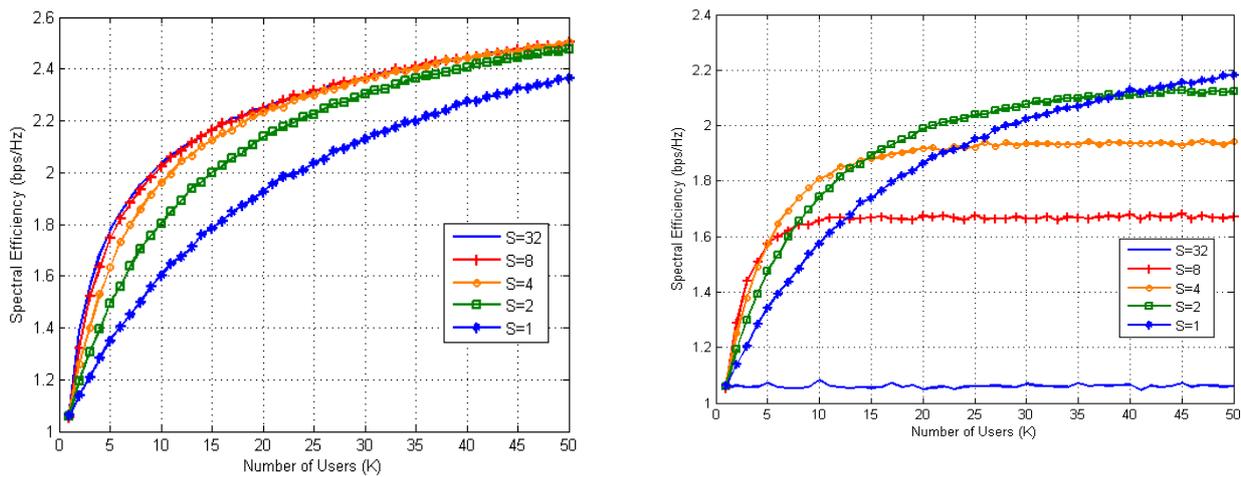


Figure 1: Throughput Performance for (a) Selective Cluster SNR feedback, (b) SCI feedback for different  $S$  values

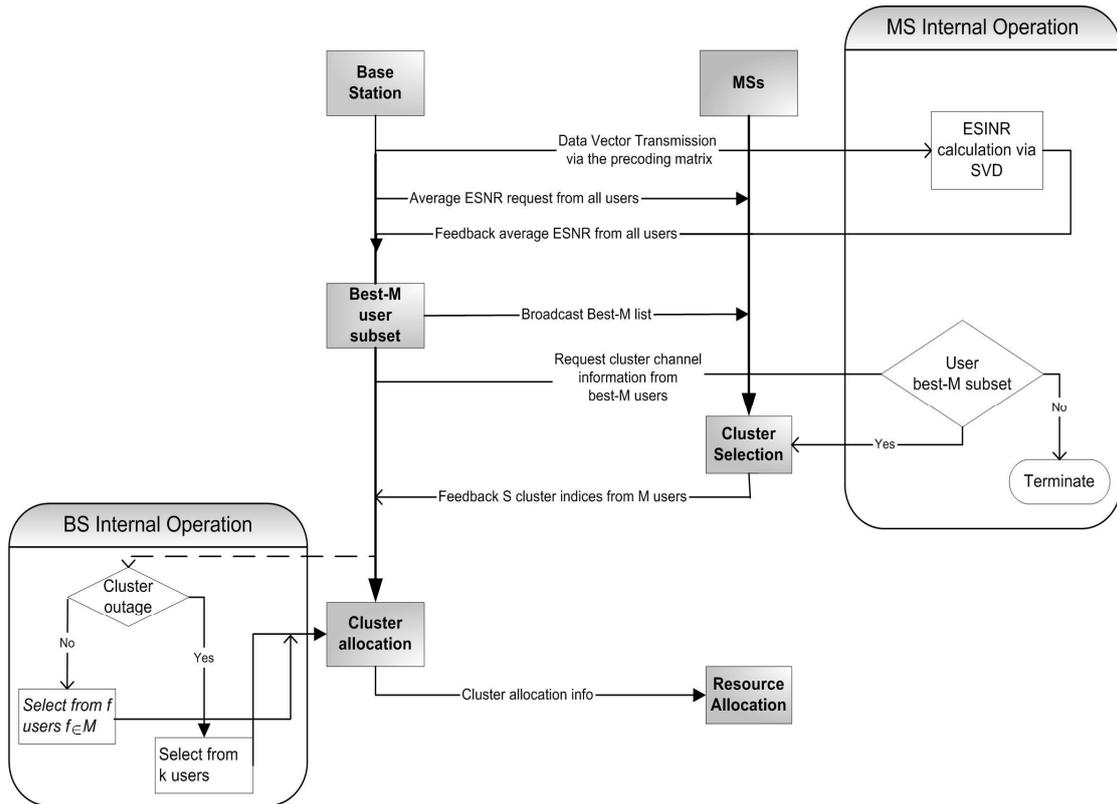


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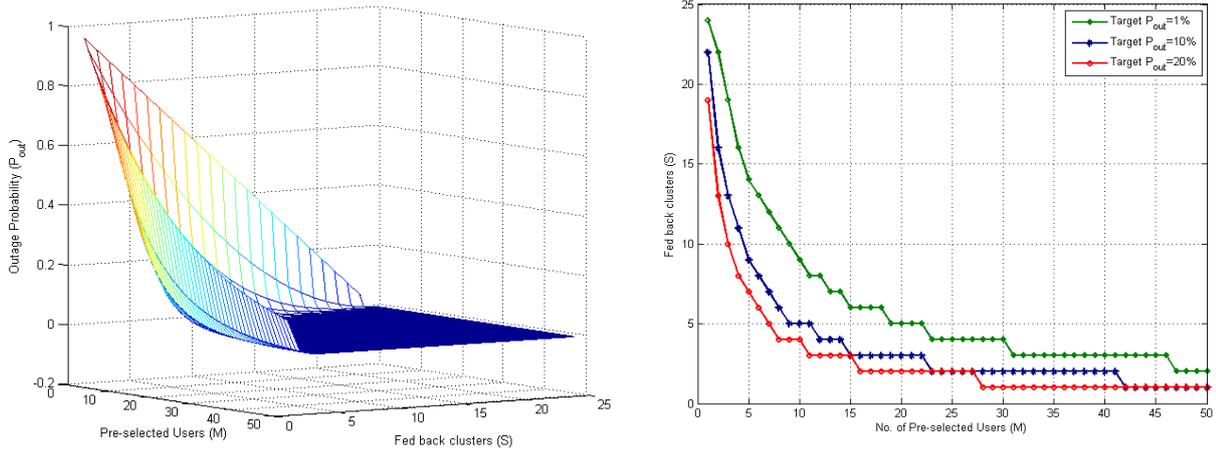


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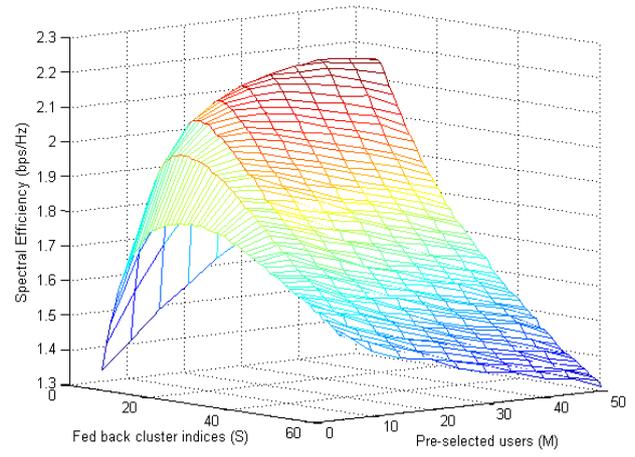
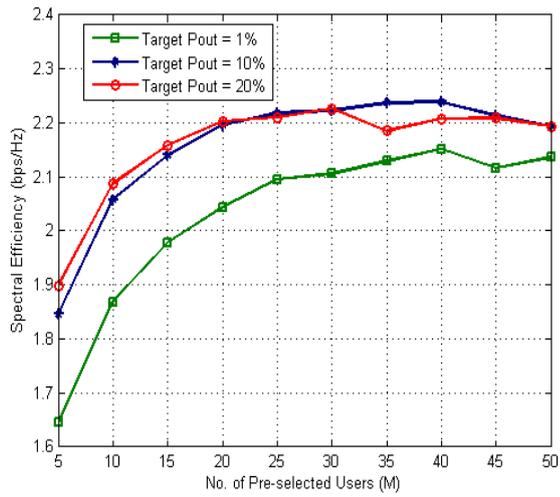


Figure 4: Average spectral efficiency of best- $M$ /SCI RB-OFDMA scheme for (a) different outage probabilities, (b) exhaustive search

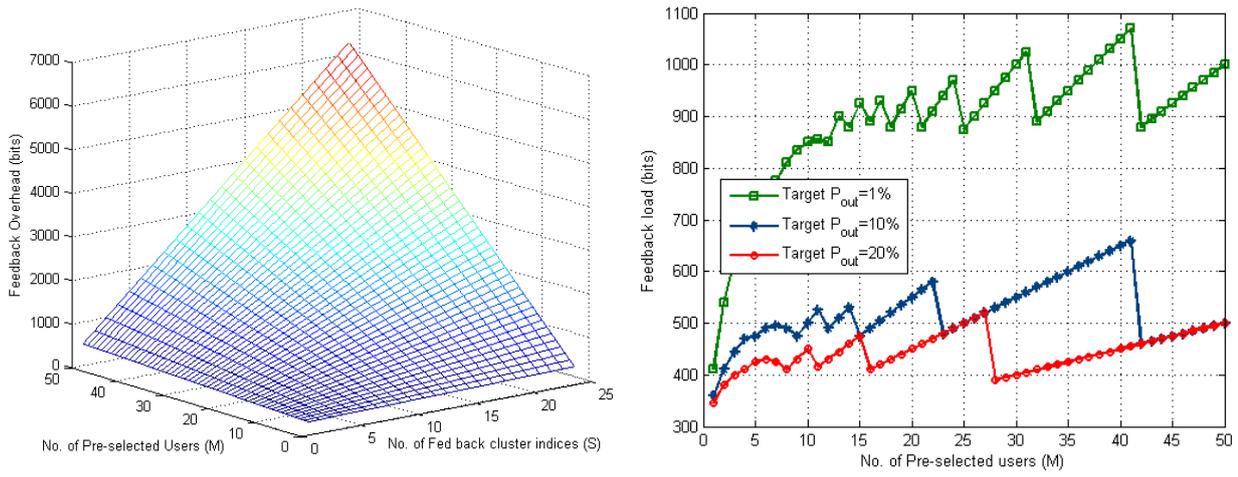


Figure 5: Feedback load for (a) SCI with best- $M$  user pre-selection, (b) best- $M$ /SCI for different outage probabilities

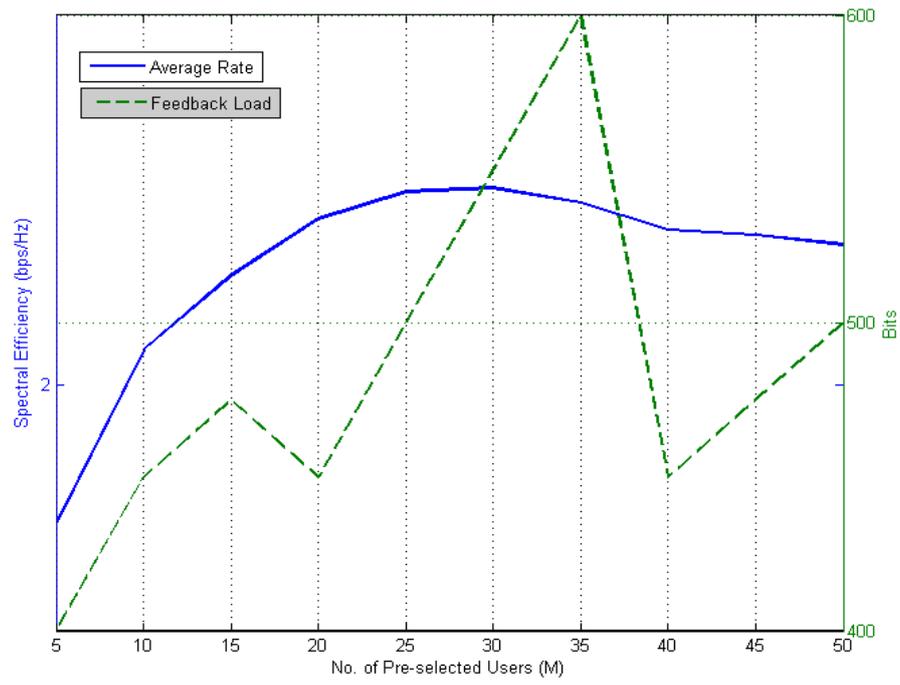


Figure 6: Throughput performance and feedback load for optimum fed back parameters

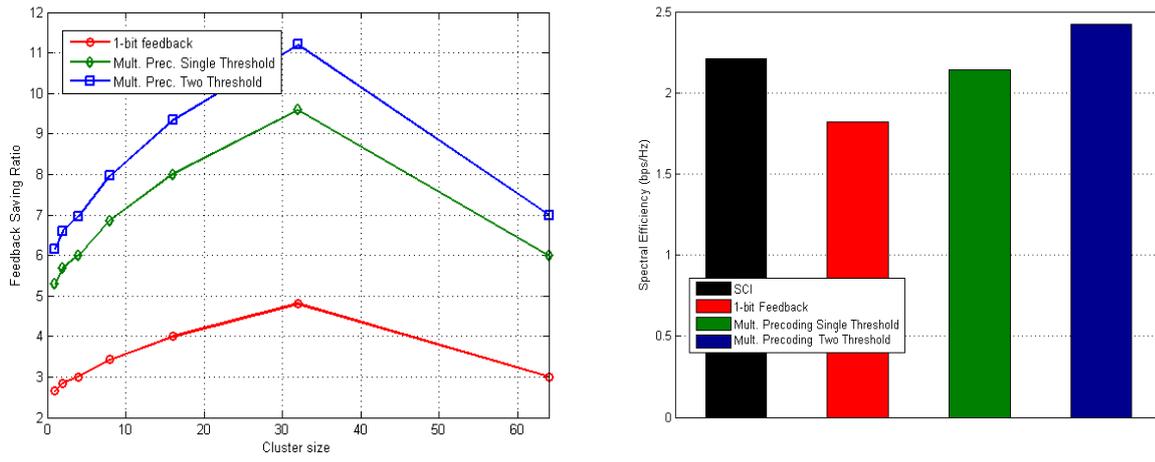


Figure 7: (a) Feedback saving of the SCI scheme over bit-based feedback schemes, (b) Spectral efficiency for  $K=50$  for reduced feedback schemes

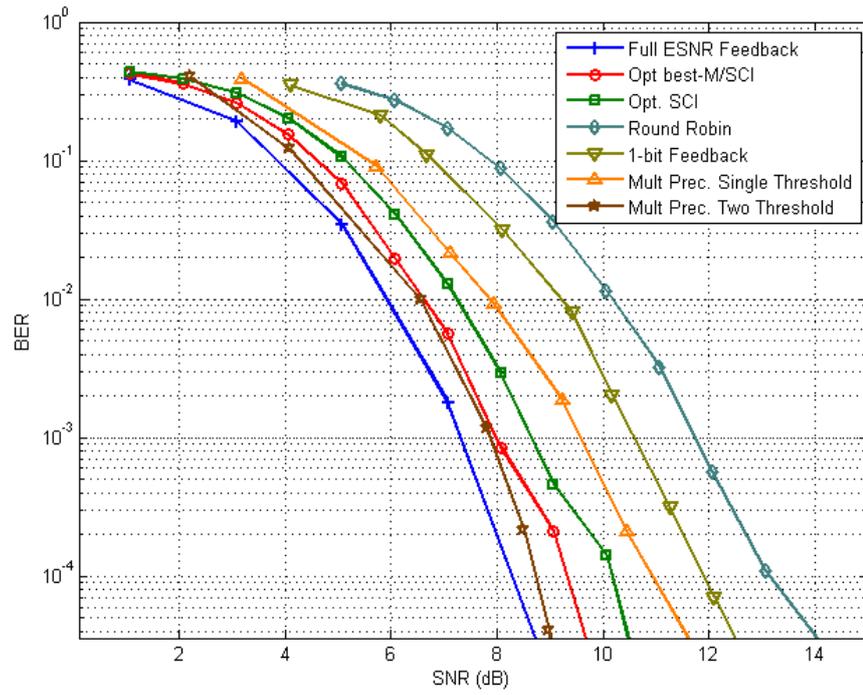


Figure 8: BER Performance Comparison among RB-OFDMA with ESNR based, SCI, best- $M$ /SCI feedback and Round Robin in channel Model  $A$  (50 MSs in the environment,  $R=32$ )

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Table 1: Lookup table of optimum  $S$  parameters for cluster size  $R=16$ Model  $A$  ( $\tau_{rms}=50ns$ )

Best-M no.	$S_{opt}$	Measured $P_{out}$ (%)	Users/cluster
5	12	24.79	1.25
10	7	20.69	1.148
15	6	12.85	1.875
20	5	10.98	2.0833
25	4	11.69	2.081
30	3	14.65	1.875
35	3	10.48	2.1875
40	3	7.92	2.5
45	3	5.63	2.8125
50	2	12.15	2.083

Model  $E$  ( $\tau_{rms}=250ns$ )

Best-M no.	$S_{opt}$	Measured $P_{out}$ (%)	Users/cluster
5	11	27.73	1.1458
10	7	20.69	1.148
15	6	12.85	1.875
20	5	11.06	2.083
25	4	11.69	2.081
30	3	14.65	1.875
35	3	10.48	2.1875
40	3	7.92	2.5
45	3	5.63	2.8125
50	2	12.15	2.083

Table 2: Parameters for the proposed OFDMA scheme

Operating Frequency	5 GHz
Bandwidth	10 MHz
FFT size	1024
Data Subcarriers ( $N_{sub}$ )	768
Sampling Period ( $T_s$ )	10 ns
Subcarrier Spacing	9.7656 KHz
OFDM Symbol Duration	12 $\mu$ s
Cluster size ( $R$ )	8/16/32
Max. Active Mobile Stations	50
Transmit Antennas ( $N_t$ )	2
Receive Antennas ( $N_r$ )	2
Channel Coding	Punctured 1/2 rate convolutional code, constraint length 7, <i>octal</i>

Table 3: Throughput and Fairness Performance for unequal channel gains

	$\sum_k R_k$	Jain's index (J)
Max. SNR	10.241	0.1569
PF ( $T_c=1000$ )	9.18	0.1687
PF ( $T_c=10$ )	8.829	0.2612
SCI	6.251	0.8708
Round Robin	3.978	0.8717