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REDUCED FEEDBACK OPPORTUNISTIC AND LAYERED RANDOM BEAMFORMING FOR MIMO-OFDMA SYSTEMS

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Invited Paper

Abstract—This paper considers a number of techniques employed in opportunistic and layered random beamforming OFDMA schemes that aim to reduce the feedback required to perform scheduling whilst also minimising the throughput degradations resulting from this reduced throughput (due to the lack of full CSI at the Base Station (BS)). Frequency response correlation among subcarriers can be exploited to group adjacent subcarriers into clusters which can then be treated as a single unit for feedback purposes to reduce the total amount of feedback. Given that these grouped subcarriers are highly correlated, good throughput performance can be preserved. In addition, it is possible to schedule clusters of size greater that 1 with a single feedback bit per cluster, achieving the same rate growth as a full CSI aware scheme. The idea of transmitting multiple weights to increase diversity has also been developed for an OFDM/OFDMA scenario where different clusters pick different weighting vectors for transmission, resulting in an overall throughput increase at the expense of only a minor increase in feedback information.

Key words — Opportunistic beamforming, layered random beamforming, MIMO-OFDMA, frequency correlation, multiple weights, 1 bit feedback.

I. INTRODUCTION

In a system with many active mobile stations, it is likely that at least one mobile station (MS) whose channel is near a peak in quality at one time and/or frequency exists, provided different mobile stations experience independent fading channels. The benefits of Multiuser Diversity (MUD) are derived by scheduling transmission resource to different MSs in multiple dimensions (time, frequency and space) in order to best exploit their diverse responses. The idea of exploiting MUD in wireless fading channels has been proposed in [1]. A method proposed in [2] introduces the Opportunistic Beamforming (OB) scheme that allows MUD gains to be realised even in environments of low scatter and mobility. The use of multiple antennas at the BS has been proposed as a means to artificially induce channel fluctuations in slow fading channels. In the downlink the BS determines the MS that has the best channel conditions for every time slot. Initially, a known training sequence $x(t)$ is transmitted from the BS multiplied by a random weighting vector $v(t) = (v_1(t),....v_N(t))^T$ to determine the instantaneous channel conditions of each user. The Signal to Noise Ratio (SNR) can be used as a measure of the instantaneous channel conditions of each terminal.

When the number of active users in the cell is small, the probability that at least one strong user exists in the system for every transmission instant reduces, providing reduced benefits of MUD. When such conditions occur, the transmission of multiple weighting vectors from the BS can provide several channel realisations to each MS, increasing the probability of a strong user for every transmission instant.

By combining the opportunistic beamforming concept and the Singular Value Decomposition (SVD) technique, [3] and [4] extend this theory to a single carrier MIMO system and develop the Random Beamforming (RB) and Layered Random Beamforming (LRB) techniques respectively. RB is capable of achieving multi-user diversity gain and spatial multiplexing gain and supports one MS transmission at any time/frequency. LRB has been developed for systems employing a linear receiver and it is capable of achieving additional multiple access by allowing different spatial layers to be separated and allocated to different MSs utilising common time and frequency resources. Therefore, LRB can achieve an additional layer spatial multi-user diversity gain but at the expense of MIMO order times more feedback. The feedback metric ESINR [4] indicates not only the eigenvalues of the MIMO channels and the mismatch between the random precoding matrix and the unitary matrix of the actual MIMO channels, but also spatial information and self-interference caused by the mismatch.

The OFDMA system is one of the most promising PHY and multiple access candidates for future communication systems and the Long Term Evolution (LTE) Third Generation Partnership Project (3GPP) has already assumed that the downlink of the air interface would be OFDMA based [5]. Its performance can be further improved by employing multiple antennas at both transmitter and receiver (MIMO). Both RB and LRB techniques are applied to an OFDMA system in [6] and performance analysis shows that they can achieve an additional spectral multi-user diversity gain compared to the single-carrier case. However, feedback on a sub-carrier basis for OFDMA systems results in a substantial overhead. A number of techniques for reducing this feedback that can be applied to opportunistic and layered random beamforming are proposed in this paper.

This paper is organized as follows. Section II describes the key parameters of the PHY OFDMA system and the channel models used for the simulation. In Section III, the Multiple Weight technique is described for OB to improve system capacity. Various feedback reduction schemes including 1 a bit feedback scheduling technique and a feedback clustering technique are also proposed for both OB and LRB-OFDMA systems. Section IV presents both numerical analysis and simulated performance of OB and LRB-OFDMA systems employing the proposed capacity achieving and feedback reduction schemes. Section V concludes the paper.

II. SYSTEM PARAMETERS AND CHANNEL MODEL

For the proposed OFDMA system, N_s data subcarriers are grouped into clusters, the number of which depends on the cluster size. For LRB, the BS allocates each spatial layer of each cluster (a group of adjacent sub-carriers) to one of the MSs depending on the feedback. A greedy algorithm is

employed for cluster allocation that maximizes overall system throughput. Scheduling details are described below:

Step 1: For every spatial layer of the MIMO channel, the BS collects the numerical average data rate $R_{k,c}^q$ [6] based on the ESINR feedback of all subcarriers in every cluster from every MS, where q is the spatial layer index. For cluster c, if the index of the starting subcarrier is n and finishing subcarrier is m, then the feedback of cluster c from MS k in frequency domain is:

$$R_{k,c}^q = \frac{1}{m-n}\sum_{s=n}^{m}\log_2\left(1+ESINR_{k,s}^q\right). \qquad (1)$$

Step 2: For spatial layer q of cluster c, the MS k^* with the highest $R_{k^*,c}^q$ is scheduled for transmission to maximize the overall system throughput.

$$R_{k^*,c}^q = \max\left\{R_{1,c}^q, R_{2,c}^q, \cdots, R_{K,c}^q\right\}. \qquad (2)$$

The parameters used in the simulation of the system in this paper are the same as those in [7] and are shown in table 1.

Table 1: Parameters for the Proposed OFDMA system

Operating Frequency	5 GHz
Bandwidth	100 MHz
FFT Size	1024
Useful Sub-carriers	768
Guard Interval Length	176
Useful Symbol Duration	10.24 μs
Channel Coding	Punctured 1/2 rate convolutional code, constraint length 7, $\{133,171\}_{octal}$

OFDM and OFDMA systems in this paper are simulated using a MIMO implementation of channels A and E of the ESTI BRAN channel models [8]. The ESTI BRAN channel models have a sampling period, $T_s = 10ns$ and an rms delay spread, τ_{rms}, ranging from $50ns$ for model A to $250ns$ for model E. In this paper, two transmission modes of a possible link adaptive scheme [7] are considered for LRB-OFDMA and they are mode 1 employing BPSK with ½ coding rate and mode 6 employing 64QAM with ¾ coding rate.

III. CAPACITY ACHIEVING AND FEEDBACK REDUCTION SCHEMES

A. Multiple Weights for Opportunistic Beamforming

When the number of active MSs in a cell is small, multiple weighting vectors can be transmitted from the BS [9] to increase diversity. The use of multiple weighting vectors introduces additional overheads on the downlink slot, which reduces the available length on the time slot used for transmission of useful data. At the beginning of each time slot, the random weighting vector $w(t) = \left(w_1(t),......,w_N(t)\right)^T$ is multiplied by a known training sequence during a small period called the minislot. The available time for transmission of useful data on the downlink reduces as the number of minislots increases. Defining L and τ as the length of the downlink slot and minislot respectively the maximum achievable throughput is:

$$T_Q(t) = (L-\tau Q)\left(\max_{q=1,...,Q,k=1,......K} R_{q,k}(t)\right) \qquad (2)$$

Clearly a very large number of weighting vectors would occupy significant amounts of the time slot. An adaptive generation of weighting vectors that depends on the number of active users and the minislot length has been proposed in [9]. In Figure 1 we show how the optimum number of weighting vectors varies for different numbers of users for a minislot/slot ratio of 5% and 10%. Clearly, as the number of users increases the inherent MUD becomes dominant, reducing the need to use multiple weighting vectors.
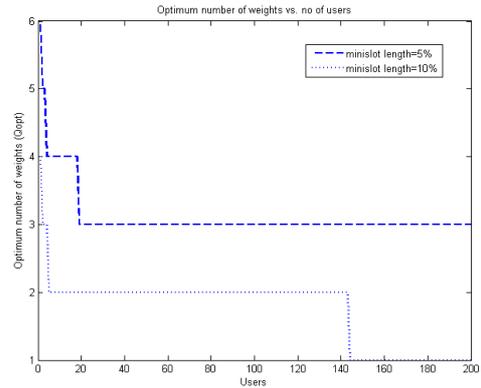

Figure 1: Optimum number of weights vs. no of users

It has been shown in [10] that in order to outweigh throughput reduction due to the overhead associated with the transmission of multiple vectors, full diversity gains should be realised through the use of multiple antennas. It has been shown that full diversity gains can be extracted using $N_t=8$ transmit antennas at the BS. Throughput gains for a single carrier scheme using the multiple weighting opportunistic beamforming configuration were presented in [11].

B. 1-Bit Feedback Scheduling

In conventional opportunistic beamforming, each MS is required to transmit back its instantaneous SNR for each scheduling interval. The BS then employs a scheduling algorithm (proportional fair [2] or greedy) to assign resources to the MS with the best channel conditions. It has been shown [12] that the same rate growth (with increasing number of users) of a fully SNR aware BS can be achieved with only 1-bit feedback information from each user. In this scheme it is suggested that each MS compares its instantaneous channel gain with a predefined threshold value and simply feeds back an indication (consisting only of 1 bit per cluster) as to whether or not the SNR of that cluster is above that threshold. After receiving indications from all MSs, the BS is now aware of which MS-clusters have acceptable channel conditions, but does not have any explicit SNR knowledge. For each cluster, the scheduler selects an MS randomly from the pool of "eligible users". However, since the scheduler can select a user from a number of eligible users, it can improve fairness by scheduling users based on their previous utilization [5]. If no eligible users exist in the system for a given time slot, the system is said to be in outage. The outage probability is defined as:

$$P_o = \left(1 - e^{-\gamma_{th}/\bar{\gamma}}\right)^K \qquad (2)$$

where γ_{th} is the threshold value and γ is the average channel gain

C. Exploiting Frequency Correlation Among Sub-carriers

The feedback load is especially crucial in OFDMA schemes where each MS transmits feedback on a sub-carrier basis. The frequency responses of the subcarriers in one cluster of an OFDMA symbol are correlated and the degree of correlation depends on the coherence bandwidth of the

channel, which is inversely proportionally to the rms delay spread of the channel. The degree of correlation is also affected by the subcarrier spacing and cluster size (CS). To utilise this frequency correlation property, feedback for OFDMA can be on a cluster basis and the CS can be appropriately chosen so that the feedback can be reduced without much degradation in throughput performance [14][15]. The correlation between the effective channel gain of sub-carrier m and n in cluster c is [15]:

$$r_{m,n} = \frac{1 - e^{-L\left(\frac{T_s}{\tau_{rms}} + j2\pi\frac{m-n}{N_s}\right)}}{\left(1 - e^{\frac{LT_s}{\tau_{rms}}}\right)\left(1 + j2\pi\frac{m-n}{T_s N_s}\right)} . \qquad (4)$$

where L is the length of guard interval, T_s is the sampling period, τ_{rms} is the expected rms delay spread and N_s is the number of data sub-carriers.

Figure 2 shows the correlation coefficient between the effective channel gains of the first and last subcarrier in a cluster as the CS increases in various ETSI BRAN channel scenarios [8]. The CS increases as $m - n$ becomes larger. For channel models experiencing different τ_{rms}, as τ_{rms} increases, the frequency responses of the subcarriers in one cluster become less correlated. For all the channel models, the frequency response correlation of the subcarriers decreases as the CS increases. If the correlation in one cluster is high (correlation coefficient is higher than 0.5), a randomly generated precoding matrix matching one subcarrier well is likely to match the other subcarriers in that cluster well, too. As a result, a suitable CS can be used as a feedback unit without degrading the overall throughput performance much relative to the case of the minimum CS.
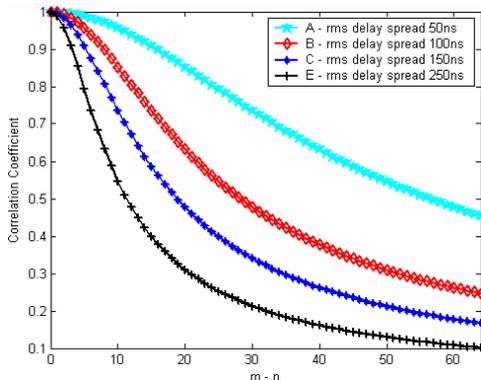

Figure 2: Correlation Coefficient between the Effective Channel Gains of Subcarriers in One Cluster in Different ESTI BRAN Channel Scenarios

IV. PERFORMANCE ANALYSIS

A. Frequency Domain Cluster Feedback

Figure 3 shows throughput results for an OB OFDMA scheme for channel A for cluster sizes R=1, 8, 16, 32 for an average SNR=0dB. It can be seen that no significant throughput degradations occur for a CS up to 32. As the CS increases, correlation of subcarriers within a cluster drops significantly and spectral efficiency is reduced. In order to increase the fading rate, clustered beamforming (CL-BF) has been suggested in [16].

The feedback reduction scheme based on exploiting the frequency correlation can also be applied to a RB or an LRB-OFDMA system. The BER performance of 12-MS RB-

OFDM/A and LRB-OFDM/A systems employing mode 6 in channel E are presented in Figure 4. A single user SM MMSE system requires no feedback and does not exploit any form of multi-user diversity and therefore has the worst performance. All the OFDMA systems adopting 1 subcarrier per cluster with the greedy algorithm outperform their related OFDM schemes (a special case of an OFDMA system which has all data sub-carriers in one cluster only) including SVD-OFDM due to significant spectral multi-user diversity gain. Therefore, the cluster size needs to be carefully chosen so that the feedback can be reduced without much performance degradation, i.e. the OFDMA systems can still exploit certain degree of frequency diversity. Since the BER performance of LRB is better than RB due to an additional layer spatial multi-user diversity gain, the performance analysis and results presented for the frequency clustering scheme consider only LRB-OFDMA. Similar simulation has also been performed for RB-OFDMA and the results show that the effect of frequency response correlation on the performance of LRB-OFDMA also applies for the RB-OFDMA case.
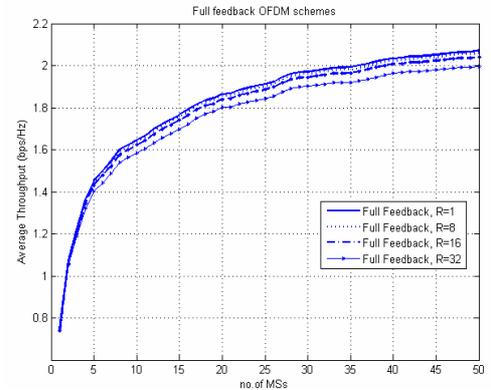

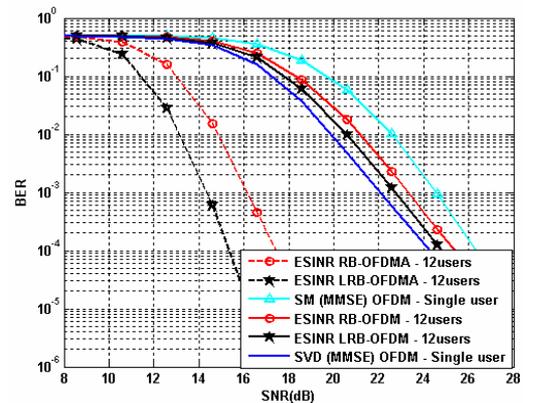Figure 3: Full feedback OFDM for different cluster sizes

Figure 4: BER Performance Comparison among RB-OFDM/A, LRB-OFDM/A and SVD OFDM in Channel E (12 MSs in the Environment)

The impact of CS on system performance in channel scenarios A and E for LRB-OFDMA at SNR = 0dB is presented in Figure 5. The data rate for different CSs increases as the number of MSs increases. In channel A, the data rate of CS up to 16 is still nearly identical to that of a CS of 1 due to the high frequency correlation of the subcarriers in the clusters (as shown in Figure 2). As a result of the greater frequency selectivity of channel E, the correlation coefficient decreases much faster as the number of subcarriers per cluster increases. Only small CSs up to 8 have performance close to that of a CS of 1. In addition, in channel E, the data rate drops

faster than the same system in channel A as the CS increases further. The data rate difference between CS of 256 and OFDM is very low in channel E and it shows that the frequency correlation of the subcarriers approaches the minimum when CS reaches 256. On the other hand, there is some frequency diversity that can be exploited when the CS reaches 256 in channel A.
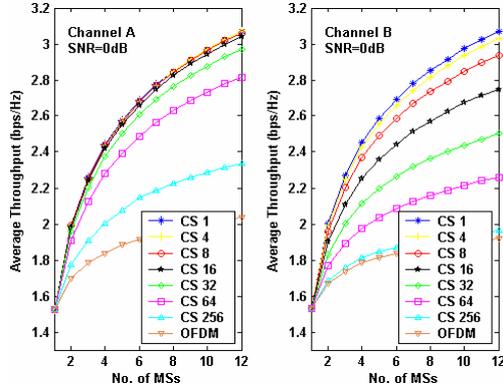

Figure 5: Average Numerical Rate of LRB-OFDM and LRB-OFDMA Employing Different Cluster Sizes at SNR=0dB in Channel A and E

To verify the numerical analysis of the impact of CS on system performance, Figure 6 shows the BER performance of LRB-OFDMA in channel A with various CSs when employing transmission mode 1. By considering a target BER of 10^{-3}, the relationship between CS and system performance can also be demonstrated by plotting the CS versus the required SNR for different transmission modes in different channels, as in Figure 7. When transmission mode 1 is employed, for a small CS, LRB-OFDMA in channel E has a steeper slope than the same system in channel A. This is because the frequency responses of the subcarriers diverge faster in channel E. As the CS increases, the slope of channel E increases very slowly and nearly becomes flat when the CS is larger than 64. In contrast, there is a gradual increase in the required SNR until the CS reaches the maximum in channel A. This result confirms that there is still some frequency correlation that can be exploited to reduce feedback and there is still some performance gain compared to the LRB-OFDM system.

The second part of Figure 7 shows the performance of the same system in different CSs adopting mode 6 in both channel A and channel E. As the CS increases, the required SNR for the system employing mode 6 increases more significantly compared to mode 1. This trend can be observed from the slope of required SNR for increasing CS is slightly steeper for mode 6 than mode 1 in both channel A and E. This is because the higher modulation and weaker coding make mode 6 more sensitive to errors and changes in channel conditions. For larger CSs, the increased SNR required by LRB-OFDMA employing mode 6 in channel A still shows a higher frequency response correlation than the same system in channel E, which loses most of the frequency diversity gain after the CS reaches 64.

Both numerical and simulation results suggests that based on the channel conditions, subcarriers of LRB-OFDMA can be grouped into clusters (if the correlation coefficient is as high as 0.5) to attain a close performance to the conventional LRB-OFDMA system but with reduced feedback. In real system design, CS may be affected by other system parameters. Generally, lower modulation and stronger coding

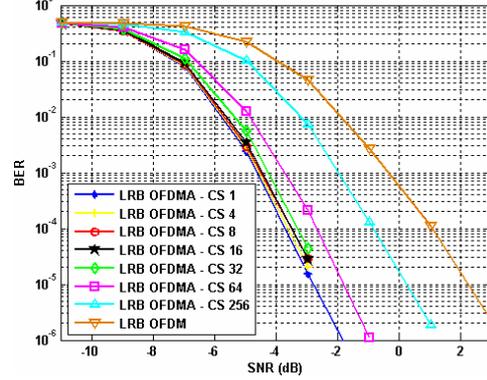schemes are more robust to errors, and therefore can support larger CSs.

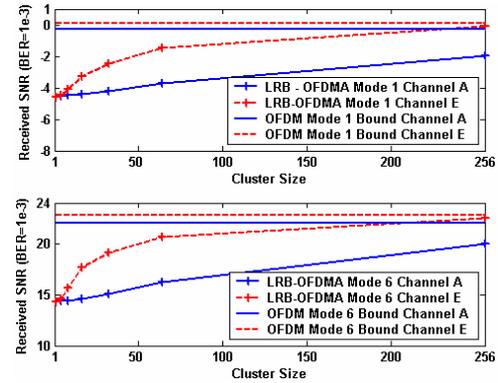Figure 6: Mode 1 LRB-OFDMA Average BER Performance of Different Cluster Sizes in Channel A

Figure 7: Mode 1 and 6 LRB-OFDM and LRB-OFDMA Required SNR for Different Cluster Sizes to Achieve Average BER 1e-3 in Channel A and E

B. Multiple Weight Opportunistic Beamforming with 1-Bit Scheduling and Frequency Domain Clustering

Despite the fact that significant throughput reduction can be achieved by treating clusters as a single feedback element, it can be seen that there is a direct tradeoff between reduced feedback and spectral efficiency. The idea of scheduling using 1-bit feedback per subcarrier has been proposed in [17]. This idea is a direct extension to the scheme proposed for the single carrier scenario. In this scheme each MS serially transmits acknowledgment bits for all the subcarriers for every time realisation. It has been argued that the same rate growth can be achieved with this scheduling algorithm. Additionally, fairness can be maintained since for each subcarrier the BS can select from a 'pool' of eligible users and can prioritize eligible MSs based on their previous utilisation.

In this paper, throughput results for the 1-bit scheduling algorithm for different CSs are presented. Figure 8 shows that 1-bit scheduling can in fact be used for a clustered implementation of OFDMA. Similarly to Figure 3, minor throughput degradations occur for up to a CS of 32. Assuming an FFT size of 1024 and a cluster size R=32, a total of 32 clusters exist in the system. Consequently the proposed scheme requires that each MS transmits 32 bits of information for every time realisation.

This paper also shows theoretical capacity results for the case of the multiple weighting OB scheme in an OFDM scenario. In accordance to the single carrier scenario suggested in [9], each MS is required to feed back SNR

values for *Q* different random weights. This approach leads to a *Q-fold* increase in feedback requirements. For the feedback design, where each subcarrier is treated as a single feedback unit, such an implementation would lead to unacceptable levels of feedback overhead. In this paper throughput results obtained from Monte Carlo simulations for a clustered OFDM configuration, using a cluster size R=16 are presented. Figure 9 presents a plot of the achievable rate using the full feedback implementation of the multiple weighting scheme in OFDM, along with the conventional OB approach, where only one weighting vector is employed, and the 1-bit scheduling approach, where the MS feeds back an indication of whether SRN exceeds the threshold value. It can be seen that significant diversity gains can be extracted using multiple weights. However, even with the use of a large CS, the use of multiple weights imposes a significant feedback load. In [10][11] ways that can significantly reduce the feedback load of an opportunistic scheme employing multiple weights with no significant throughput degradations have been proposed for a single carrier implementation.
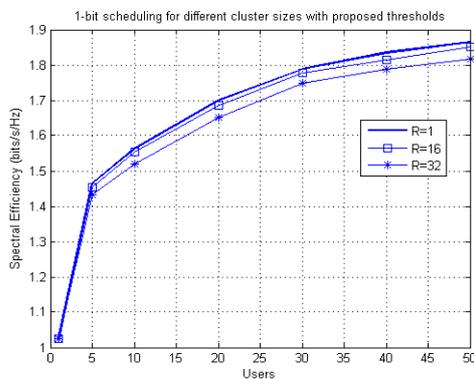

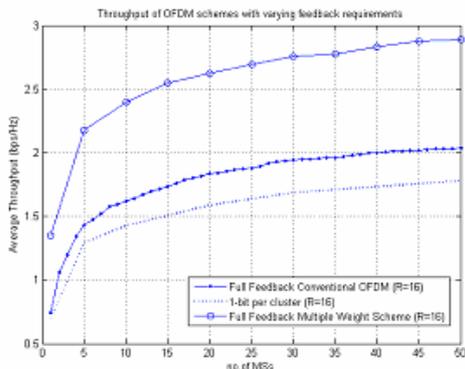Figure 8: 1-bit scheduling for different cluster sizes

Figure 9: Throughput of OFDM with varying feedback requirements

V. Conclusions and Future Work

By employing the opportunistic beamforming and layered random beamforming techniques in combination with OFDMA, systems are capable of effectively exploiting multi-user diversity gains. Particularly, the LRB scheme is able to achieve an additional layer spatial multi-user diversity gain at the expense of a requirement, in principle, to have feedback of ESINR information for every sub-carrier and layer.

In this paper, techniques that can be applied to opportunistic and layered random beamforming OFDM schemes in order to limit the load on the feedback channel, required to perform scheduling, have been outlined. It has been shown that frequency response correlation among subcarriers can be exploited to group adjacent subcarriers into clusters to reduce the actual feedback required while still maintaining good throughput performance. Additionally, it is possible to schedule clusters of size greater that 1 with a single feedback bit. The idea of transmitting multiple weights has also been developed for a multicarrier scenario.

Future work includes the integration of the use of multiple weights to a bit-based scheduling scheme for OFDM systems. Proportional fair scheduling can be applied in order to achieve a more fair resource allocation. Additionally, reduced feedback scheduling algorithms need to be developed to consider QoS requirements of different traffic classes.

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