A Low-Complexity CDD-based Frequency Selective Scheduling with Efficient Feedback for Downlink OFDMA Systems

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***Abstract*—Cyclic-delay diversity (CDD) based frequency-selective scheduling is an effective technique to increase system capacity with low complexity. By increasing the channels' frequency selectivity with cyclic delays, the merit of multi-user diversity can be exploited more effectively in the system. This paper aims to optimize the design of the CDD-aided frequency-selective scheduling for downlink OFDMA systems. First, a low-complexity search of CD-values is proposed that results in a higher system capacity than the existing methods. Second, a new feedback method is proposed based on the principle of proportional-fair, where users who currently enjoy more downlink source are allotted less uplink resource for feedback. The method is shown to provide a better tradeoff between system capacity and fairness than the traditional methods, under a fixed feedback overhead. The effectiveness of the proposed method is verified by extensive computer simulations.**

I. INTRODUCTION

OFDM (orthogonal frequency-division multiplexing) is an effective modulation/multiplexing scheme to counteract inter-symbol interference (ISI) incurred in high data-rate transmissions. By using parallel orthogonal sub-carriers along with cyclic-prefix, ISI can be removed completely as long as the cyclic-prefix is larger than the maximum delay spread of the channel. Furthermore, OFDMA (orthogonal frequency-division multiple access), an OFDM-based multiple access where users use different sets of sub-carriers (sub-channels) for communication, has been widely regarded as one of the most promising multiple access schemes for high data-rate mobile cellular systems. OFDMA has been adopted in the 3GPP-LTE [1] and the IEEE 802.16e specification [2].

Cyclic-delay diversity (CDD) is a simple transmit diversity technique where different cyclic delays are applied to antennas to create frequency selectivity in the channel and hence increase diversity order. CDD is attractive because it can be used with any number of transmit antennas and applied to the existing systems without modifying the receiver [3]-[11]. In particular, CDD has been employed along with channel coding to improve link performance [3]-[7] and along with frequency-selective scheduling to increase system capacity of the OFDMA systems [8]-[11]. For the latter, in [8], a frequency-selective scheduling based on single-degree CDD (SD-CDD) was proposed for the OFDMA downlink systems, where a predetermined collection of CD-value sets is used for all users. In [9] and [10], a book of CD-value sets, called multi-degree cyclic delay diversity (MD-CDD), was proposed to improve the performance of SD-CDD, where the best CD-value set from the book is selected by the user. In [9], the design of the book of CD-value sets is randomly generated and thus called multi-degree random cyclic-delay diversity (MD-RCDD), while in [10] the author improved MD-RCDD by using an adaptive method for the design of the book and was named multi-degree adaptive cyclic-delay diversity (MD-ACDD). And, in [11], an exhaustive search of the optimal CD-value set was proposed, but with a complexity increasing exponentially with the number of the transmit antennas and/or the size of CD-value sets.

In this paper, a new CDD-based frequency-selective scheduling is proposed for the OFDMA downlink systems. Firstly, a low-complexity search method, called antenna-wise sequential search (AWSS), is devised to optimize the CD-values for a sub-channel. Under the same feedback overhead, the proposed method provides a higher system capacity than the MD-ACDD method in [10] and has a lower complexity than the exhaustive search method in [11]. Secondly, a new feedback method of CD-values and sub-channel capacity is proposed based on the principle of proportional fair, where less uplink resource is allocated to users who have already enjoyed more downlink resource up to the previous scheduling. The new feedback method provides a better tradeoff between system capacity and user fairness than the traditional methods under the same feedback overhead.

The rest of the paper is organized as follows. Section II describes the system and channel models. Section III gives the proposed method for the CD-value search along with an analysis on the computational complexity. Section IV presents the new feedback method. And, simulation results and conclusion are given in Section V and Section VI, respectively.

II. SYSTEM AND CHANNEL MODELS

We consider a single-cell OFDMA downlink system with M mobile stations (MSs). The frequency band which consists of N_{FFT} sub-carriers is divided into N_S sub-channels with $N_C = N_{FFT} / N_S$ adjacent sub-carriers in each sub-channel. The base station (BS) is equipped with n_t transmit antennas and MS with a single receive antenna. Fig. 1 is the system setup. At the MS side, every MS estimates the channel state information of sub-channels, determines CD-values and the associated capacity of each sub-channel, and reports some of them to the BS before the next scheduling instant. At the BS, scheduling is performed based on the feedback information provided by MSs; then data from the scheduled MSs are cyclically delayed (performed in the frequency domain) and OFDM-modulated before passed to antennas for transmission.

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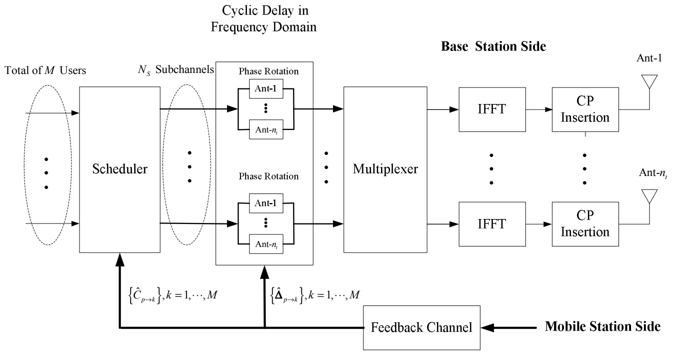


Figure 1. System architecture of the OFDMA downlink system with CDD-aided frequency-selective scheduling

Consider the signal destined to MS k who is assumed to use all sub-channels for notation simplicity. (In real OFDMA systems, sub-channels are shared by the scheduled MSs, and data from those MSs are multiplexed together before passed to the IFFT.) Let $S_k(m),\ m = 0,\cdots,N_{FFT}-1$ be the data symbols and Δ_i the CD-value for antenna i. Using CDD, the transmitted OFDM signal from antenna i is expressed by

$$s_i(n) = \frac{1}{\sqrt{N_{FFT}}} \sum_{m=0}^{N_{FFT}-1} e^{-j\frac{2\pi m \Delta_i}{N_{FFT}}} S_k(m) e^{j\frac{2\pi mn}{N_{FFT}}}, \quad n = -N_g,\cdots,N_{FFT}-1, \tag{1}$$

where N_g is the length of cyclic prefix.

The channel from antenna i to MS k is modeled by the impulse response $g_k \cdot h_{i\to k}(l)$, $l = 0,\cdots,L$, where g_k denotes the channel loss due to path-loss and shadowing, $\{h_{i\to k}(l)\}_{l=0}^{L}$ are the tap gains to modeling the small-scale fading of the channel, and $L+1 \le N_g$ is the length of the channel. For the Rayleigh fading as is considered here, $\{h_{i\to k}(l)\}_{l=0}^{L}$ are modeled as mutually independent complex Gaussian random variables with zero mean and variance $\sigma_{k,l}^2$. In particular, an exponential multi-path intensity profile is used with $\sigma_{k,l}^2 = \sigma_l^2 = \sigma_0^2 \cdot \exp(-lT_s/T_{RMS})$, where T_{RMS} is the root-mean square delay spread, T_s is the sampling time of OFDM signals, and σ_0^2 is set to be $\sigma_0^2 = (1-\exp(-T_s/T_{RMS}))$ in order to have $\sum_{l=0}^{L}\sigma_l^2 = 1$. Furthermore, $\{h_{i\to k}(l)\}_{l=0}^{L}$ are assumed i.i.d. (independent and identically distributed) among different antennas and different MSs and remained unchanged over a scheduling period (for low-mobility users).

At MS k, the received signal is, after cyclic-prefix removal and taking FFT,

$$Y_k(m) = g_k H_k(m) S_k(m) + N_k(m), \quad m = 0,\cdots,N_{FFT}-1 \tag{2}$$

where

$$H_k(m) = \frac{1}{\sqrt{n_t}} \sum_{i=1}^{n_t} e^{-j\frac{2\pi m \Delta_i}{N_{FFT}}} H_{i\to k}(m), \tag{3}$$

$$H_{i\to k}(m) = \sum_{n=0}^{N_{FFT}-1} h_{i\to k}(n) e^{-j\frac{2\pi mn}{N_{FFT}}}, \tag{4}$$

$\{N_k(m)\}$ are i.i.d. Gaussian variables with zero mean and variance $\sigma_N^2 = \mathrm{E}\left[|N_k(m)|^2\right]$, $\mathrm{E}[\bullet]$ denotes the operation of taking expectation, and $h_{i\to k}(n) = 0,\ n = L+1,\cdots,N_{FFT}-1$.

III. SEARCH OF CYCLIC-DELAY VALUES

The capacity of a sub-channel will be used as the performance index in search of the best CD-value set for that sub-channel. Assuming that sub-channel p is to be scheduled to MS k, $1 \le p \le N_S$, the capacity of the sub-channel is

$$C_{p\to k} = \sum_{m=(p-1)N_C}^{pN_C-1} \log_2\left(1 + g_k^2 |H_k(m)|^2 \cdot \sigma_S^2 / \sigma_N^2\right) \quad \text{bps/Hz}, \tag{5}$$

where $H_k(m)$ is evaluated in (3) and (4) with Δ_i replaced by $\Delta_{p\to k}^i$, $i = 1,\cdots,n_t$, and $\sigma_S^2 = \mathrm{E}\left[|S_k|^2\right]$ is the average power of data symbol. The optimal set of CD-values is the one to maximize $C_{p\to k}$, i.e.,

$$\hat{\Delta}_{p\to k} = \arg \max_{\Delta_{p\to k} = \{\Delta_{p\to k}^1,\cdots,\Delta_{p\to k}^{n_t}\}} C_{p\to k}. \tag{6}$$

Without loss of generality, we assume $\Delta_{p\to k}^1 = 0,\ \forall p,k$. In practice, $\Delta_{p\to k}^i$ and $C_{p\to k}$ must be quantized before being reported to BS for scheduling due to the limitation of finite feedback overhead. Define $\Lambda \doteq \{Q_\Delta[\Delta_{p\to k}^i]\},\ i = 1,\cdots,n_t$ and $\Xi \doteq \{Q_C[C_{p\to k}]\}$ be the sets of quantized CD-values and capacity values, respectively, where $Q_\Delta[\bullet]$ and $Q_C[\bullet]$ denote the operations of quantization for reducing the feedback overhead. Λ and Ξ will be assumed to be the same for all p and k. In addition, $|\Lambda| = 2^{b_\Delta}$, and $|\Xi| = 2^{b_C}$, where $|\mathrm{X}|$ denotes the cardinality of X, and b_Δ and b_C are the feedback bit numbers of a CD-value and a sub-channel capacity, respectively. Taking into consideration of the quantization effects, the optimization in (6) becomes

$$\hat{\Delta}_{p\to k} = \arg\left\{\max_{\Delta_{p\to k}\in\Lambda^{n_t}} C_{p\to k}\right\}, \tag{7}$$

where Λ^{n_t} is the n_t-fold Cartesian product of Λ. As is clear in (5)-(7), $C_{p\to k}$ is a highly nonlinear function of $\{\Delta_{p\to k} \in \Lambda^{n_t}\}$, and generally it is difficult to solve (7) analytically. Theoretically, $\hat{\Delta}_{p\to k}$ can be found through an exhaustive search, its complexity, however, increases exponentially with n_t and/or $|\Lambda|$. After $\hat{\Delta}_{p\to k}$ is obtained, it is feedback along with the quantized capacity $\hat{C}_{p\to k} = Q_C[C_{p\to k}(\hat{\Delta}_{p\to k})] \in \Xi$.

A. *Antenna-Wise Sequential Search* (*AWSS*)

In this sub-section, a low-complexity method, called antenna-wise sequential search (AWSS), is proposed in search of the best set of CD-values efficiently. The proposed method outperforms the existing ones and provide good tradeoff between performance and complexity under different n_t and $|\Lambda|$, as is to be shown in Section V.

The basic idea is that the best CD - value of an antenna is searched one after another by using an exhaustive search, given the best CD-values obtained previously. As a result, the complexity is proportional to $|\Lambda|\cdot(n_t-1)$ rather than $|\Lambda|^{(n_t-1)}$ as in the multi-dimensional exhaustive search method. (Here, we have utilized the simplification of $\Delta^1_{p\to k}=0$.) In particular, starting from $i=2$, the optimal CD-value $\hat{\Delta}^i_{p\to k}$ for sub-channel p is obtained by

$$\hat{\Delta}^i_{p\to k}=\arg\left\{\max_{\Delta^i_{p\to k}\in\Lambda} C_{p\to k,i}\right\},\ i=2,\cdots,n_t, \tag{8}$$

where

$$C_{p\to k,i}=\sum_{m=(p-1)N_C}^{pN_C-1}\log_2\left(1+g_k^2\left|\frac{1}{\sqrt{i}}\left(H_{k,i-1}(m)+e^{-j\frac{2\pi m\hat{\Delta}^i_{p\to k}}{N_{FFT}}}H_{i\to k}(m)\right)\right|^2\frac{\sigma_S^2}{\sigma_N^2}\right), \tag{9}$$

and

$$H_{k,i-1}(m)=\sum_{l=1}^{i-1}e^{-j\frac{2\pi m\hat{\Delta}^l_{p\to k}}{N_{FFT}}}H_{l\to k}(m) \tag{10}$$

B. Complexity Analysis

The computational complexity of the proposed algorithms is summarized in Table I, including the number of real multiplications and additions. The complexity of multi-dimensional exhaustive search (ES) is also analyzed for comparison purpose. For ES, the complexity of searching a CD-value set is calculated by counting the additions and multiplications needed in (5). Since there are total of $|\Lambda|^{(n_t-1)}$ CD-value sets to be evaluated, the total complexity is $|\Lambda|^{(n_t-1)}$ times of the complexity of a CD-value set. For AWSS, the complexity per antenna is evaluated by counting the additions and multiplications needed in (9) and (10), and the total complexity is (n_t-1) times of the complexity per antenna. The complexity comparison of different methods will be given for an example of practical interest in Section V.

TABLE I. Computational complexity of different CD-value search methods

Computational Complexity	ES	
Number of real additions	Per CD- value set	$N_C+4n_tN_C-1$
	Total	$\lvert\Lambda\rvert^{(n_t-1)}(N_C+4n_tN_C-1)$
Number of real multiplications	Per CD- value set	$N_C(5+6n_t)$
	Total	$\lvert\Lambda\rvert^{(n_t-1)}N_C(5+6n_t)$
	AWSS	
Number of real additions	Per antenna	$\lvert\Lambda\rvert(7N_C-1)$
	Total	$(n_t-1)\lvert\Lambda\rvert(7N_C-1)$
Number of real multiplications	Per antenna	$\lvert\Lambda\rvert(9N_C)$
	Total	$(n_t-1)\lvert\Lambda\rvert(9N_C)$

IV. FREQUENCY SELECTIVE SCHEDULING

The proportional-fair scheduling will be employed along with the proposed CD-value search and feedback methods to improve the system performance. Proportional-fair scheduling has been well known for its ability to provide a good balance between system capacity and user fairness [12].

A. Proportional-Fair Scheduling

The proportional-fair scheduling proposed in [12] is employed in this work, where sub-channel p will be scheduled to MS k if

$$k=\arg\left\{\max_j\frac{r_{p\to j}}{R_j},j=1,...,M\right\}, \tag{11}$$

where $r_{p\to j}=\hat{C}_{p\to j}B_S$ is the achievable data rate if sub-channel p is scheduled to MS j , $\hat{C}_{p\to j}$ is the quantized sub-channel capacity achieved using $\hat{\Delta}_{p\to j}$, B_S is the sub-channel bandwidth, and R_j is the average rate of MS j up to the last scheduling. Let $I(j)$ be the indicator function that MS j is scheduled at the present scheduling, that is $I(j)=1$ if MS j is scheduled, and $I(j)=0$ otherwise, and S_j be the set of sub-channels scheduled to MS j . Then, R_j is updated as follows after the scheduling.

$$R_j\leftarrow\frac{(W-1)R_j+I(j)\sum_{p\in S_j}r_{p\to j}}{W}, \tag{12}$$

where W is the average window size.

B. New Feedback Method

Clearly, $\hat{\Delta}_{p\to j}$ and $\hat{C}_{p\to j}$ have to be reported by MS j in order for the scheduler at BS to work properly. Theoretically, if $\hat{\Delta}_{p\to j}$ and $\hat{C}_{p\to j}$ of all sub-channels are reported by every user, the scheduler will have the best performance. However, the overhead, given by $MN_S\left((n_t-1)b_\Delta+b_C\right)$ bits, might be too large in practical systems. Here, a new feedback method is proposed, aiming to optimize the tradeoff between the system capacity and fairness under a fixed feedback overhead. In the method, the total number of sub-channels to be reported by all users is fixed at N_{total} , and, thus, the feedback overhead is fixed at $N_{total}\left((n_t-1)b_\Delta+b_C\right)$ bits. Our problem is then to allot each MS with a certain number of sub-channels for reporting so that the system has the best system capacity vs. fairness tradeoff.

Define $N_{S,k}$ be the number of sub-channels allotted to MS k for reporting. The basic idea is that if MS k has a relatively low average rate R_k up to the previous scheduling, then at the next scheduling, it is more likely that MS k would be scheduled following the proportional-fair principle. Therefore, it will be beneficial if MS k is allowed to report more sub-channels. Based on this idea, the ratio of sub-channel reporting by MS k is proposed as follows.

$$\alpha_k=\left(\frac{1/R_k}{\sum_{j=1}^{M}1/R_j}\right)^\beta\Bigg/\sum_{i=1}^{M}\left(\frac{1/R_i}{\sum_{j=1}^{M}1/R_j}\right)^\beta, \tag{13}$$

where β is a control parameter to control the ratio. Note that, $\sum_{k=1}^{M}\alpha_k = 1$, and $\alpha_k = 1/M$ if $R_i = R_j, \forall i,j$ and/or $\beta = 0$. Given α_k, then the best $N_{S,k} = \min(\text{round}(\alpha_k N_{total}), N_S)$ sub-channels of MS k will be reported to the BS, where $\text{round}(x)$ is the operation of rounding x to the nearest integer, and $\min(a,b)$ is the selection of the minimum value between a and b. Besides, the pitfall that $\sum_{j=1}^{M} N_{S,j}$ may exceed N_{total} is avoided.

V. SIMULATION RESULTS

In this section, the performance of the proposed method is evaluated for an OFDMA downlink system. Table II summarizes the system parameters, where the channel coherence bandwidth $(\Delta f)_c$ is defined as $(\Delta f)_c \doteq 1/(5T_{RMS})$. The channel length is set to be $L = 10 \cdot T_{RMS}/T_s = 2 \cdot \gamma \cdot N_{FFT}/N_C$, and the total number of sub-channels N_{total} to be reported by all MSs is set to be $N_{total} = \mu M N_S$, where $0 < \mu \le 1$ is the reporting ratio. In addition, in all figures, $\text{SNR} \doteq |g_k|^2 \cdot \sigma_S^2 / \sigma_N^2$.

Firstly, the selection of β in (13) is investigated for the proposed feedback method. Fig. 2 shows sample results of (AWSS, EF) with $n_t = 2$, $\gamma = 1$, $\mu = 0.2$ and $W = 20$, where (X, EF) is to denote the scheme with X as the CD-value search method and the proposed efficient feedback as the feedback method. In this figure, the system capacity and user fairness are employed to evaluate the system performance. The concept of short-term fairness in [12]-[13] is adopted for evaluating the users' fairness because it gives the measure under a short time scale. In particular, the short-term fairness F in [12] is adopted.

$$F = \min_{t \in \{0, \tau, 2\tau, \cdots, T_{sim}\}} F(t), \tag{14}$$

and

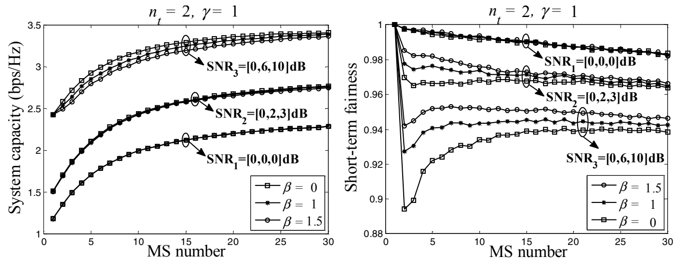
$$F(t) = \frac{\left|\sum_{j \in A} R_j(t)\right|^2}{|A| \sum_{j \in A} R_j^2(t)}, \tag{15}$$

where $R_j(t)$ is the average rate received by MS j at the time interval $[t, t+\tau)$, τ is the observation window size, T_{sim} is the total simulation time, and A is the set of MSs with nonzero buffers in $[t, t+\tau)$. In our case, since all users are assumed to have full buffer, $|A| = M$. In addition, $\tau = 20T_{OFDM}$ (20 OFDM symbols) and $T_{sim} = 200T_{OFDM}$. Furthermore, in all simulations, users are divided into three classes with users in the same class having the same received SNR. The set of SNRs are denoted by the three-tuple $\mathbf{SNR} = [\text{SNR}_1, \text{SNR}_2, \text{SNR}_3]$ (in dB).

Fig. 2 (a) and Fig. 2 (b) show the system capacity and F with different β's for three cases : $\mathbf{SNR_1} = [0,0,0]$, $\mathbf{SNR_2} = [0,2,3]$, $\mathbf{SNR_3} = [0,6,10]$. The results are obtained with an average over 30 realizations each with the simulation time

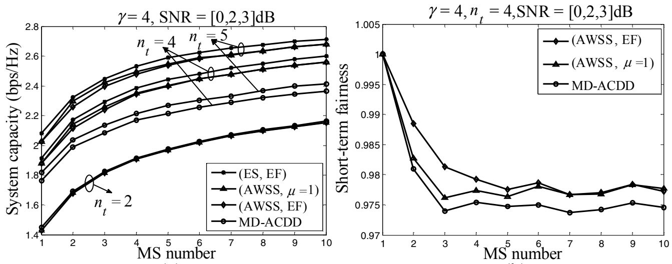
TABLE II. System Parameters

Parameter	value
System bandwidth	10 MHz
FFT size, N_{FFT}	1024
Number of data sub-carriers	720
Number of sub-channels, N_S	30
Number of sub-carriers per sub-channel, N_C	24
Number of transmit antennas at BS, n_t	2, 4, 5
Useful OFDM symbol time, $T_{FFT} = N_{FFT} \cdot T_s$	91.4 μs
Guard time, $T_{FFT}/8$	11.4 μs
Sub-carrier spacing, $1/T_{FFT}$	10.94 KHz
Sub-channel bandwidth, $B_S = N_C \cdot 1/T_{FFT}$	262.56 KHz
Channel selectivity rate, $\gamma \doteq B_S/(\Delta f)_c$	1, 4



(a) (b)

Figure 2. The comparisons of (a) system capacity, and (b) fairness for the proposed AWSS with efficient feedback under different **SNR**'s and β's.



(a) (b)

Figure 3. The comparisons of (a) system capacity, and (b) fairness for the proposed AWSS, ES, and MD-ACDD.

of $T_{sim} = 200T_{OFDM}$. For the case of $\mathbf{SNR_1} = [0,0,0]$, since all users have the same received SNR, the average rate received by each user is approximately the same, and therefore, fairness is basically not affected with different β (see (13)). In the case of $\mathbf{SNR_2} = [0,2,3]$, however, users in different classes will have different average rate with $\beta = 0$, and that reduces the user fairness. And, as is expected, using a large β in this case improves the user fairness. Note that no much loss in the system capacity is observed in this case. For the case of $\mathbf{SNR_3} = [0,6,10]$, however, a lager loss in system capacity is observed with $\beta = 1.5$ although the user fairness is improved significantly. The reason that the user fairness is improved with a larger β is attributed to that a larger portion of the reporting resource is allocated to users who have received less data rate. In the rest of this section, the case of $\mathbf{SNR_2} = [0,2,3]$ with $\beta = 1$ is simulated exclusively. $\beta = 1$ provides a good balance between system capacity and user fairness according to our extensive simulations including those not shown here.

In Figs. 3, the proposed AWSS method is compared with MD-ACDD in [10] and ES in [11]. In MD-ACDD, first, every MS finds a set of CD-values for each sub-channel, aiming to maximize the capacity of the center sub-carrier. (As a result, the method is optimal only if all sub-carriers of a sub-channel fall within the coherence bandwidth.) The set of CD-values is then feedback by each MS to the BS for every sub-channel. Second, after the BS receives the CD-value sets from all MSs, a book of CD-value sets of size Z is established by choosing the Z CD-value sets that have been used most frequently among all MSs, and the book of CD-value sets is broadcasted periodically. Finally, every MS selects the CD-value set that maximizes the capacity for each sub-channel and reports the index of the selected CD-value set to the BS along with the capacity of that sub-channel. In MD-ACDD, all sub-channels are reported by every MS.

For a fair comparison, we equalize the feedback overhead of the proposed AWSS, MD-ACDD and ES methods, that is,

$$M \cdot N_S \cdot (\log_2 Z + b_C) = N_{total} \cdot ((n_t - 1) \cdot b_\Delta + b_C), \quad (16)$$

and

$$\mu = \frac{N_{total}}{MN_s} = \frac{(\log_2 Z + b_C)}{((n_t - 1) \cdot b_\Delta + b_C)}. \quad (17)$$

In the simulations, $b_C = 8$ bits, $b_\Delta = 4$ bits, $\log_2 Z = 4$ bits, and $\mu = 1,\ 3/4,\ 3/5,\ 1/2,$ for $n_t = 2,\ 3,\ 4,\ 5$, respectively. The system capacity and fairness are compared in Fig. 3 (a) and (b), respectively, for the case of $\gamma = 4$.

In Fig. 3 (a), the ES has the highest system capacity, followed by AWSS then MD-ACDD. For the complexity comparison, AWSS has the complexity of 1.04×10^4 multiplications for $n_t = 4,\ b_\Delta = 4$, which is lower than ES that has the complexity of 2.85×10^6 multiplications. As the case of $n_t = 5,\ b_\Delta = 4$, the complexity of AWES is slightly increased to 1.38×10^4 multiplications, whereas the complexity of ES is exponentially increased to 5.51×10^7 multiplications.

Also shown in Fig. 3, the proposed AWSS method outperforms MD-ACDD by a large margin for $n_t = 4$ and 5; 8.2% and 11.2% improvements are observed for AWSS with $n_t = 4$ and 5, respectively for $M = 10$. The improvement by the proposed method can be attributed to two causes. First, the size of the book of CD-value sets is Λ^{n_t-1} in our method which can be much larger than Z in MD-ACDD for $n_t > 3$. Second, the proposed AWSS method is to maximize the sub-channel capacity rather than the capacity of the center sub-carrier as in MD-ACDD. For the case of $n_t = 2$, as is shown, the improvement becomes much smaller because in this case the books of CD-value sets are the same in the proposed AWSS method, ES, and MD-ACDD.

Fig. 3 (b) compares the performance of fairness between the proposed method and MD-ACDD for the case of $n_t = 4$. As can be seen, the proposed method have a better fairness over MD-ACDD because of the new feedback method provides a better tradeoff between system capacity and fairness. In Fig. 3, the proposed methods with $\mu = 1$ are also included for comparison purpose. Recall that in the case $\mu = 1$, all the sub-channels are reported by every MS, and therefore the feedback overhead is much higher. From Fig. 3 (a) and (b), it is seen that using $\mu = 1$ only provides very small improvement in system capacity while suffers from slight loss in fairness, as compared to the case of $n_t = 4$ with $\mu = 3/5$.

VI. Conclusion

In this paper, a low-complexity CDD-based frequency selective scheduling is proposed for the OFDMA downlink systems, aiming to optimize the system performance. A new CD-value search method, namely AWSS, is proposed along with a new feedback method. The proposed AWSS method provides a much higher system capacity than the MD-ACDD method in [10] for $n_t \geq 3$, and has a much lower computational complexity than the multi-dimensional exhaustive method in [11] with only a slight loss in the system capacity. In addition, the new feedback method is capable of providing better tradeoff between system capacity and user fairness than the conventional feedback methods.

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