Optimization of Cyclic-Delay Diversity Aided Frequency-Selective Scheduling in OFDMA Downlink Systems

Yu-Fan Chen, Wern-Ho Sheen, *Member, IEEE*, and Li-Chun Wang, *Fellow, IEEE*

***Abstract*—Cyclic-delay diversity (CDD)-aided frequency-selective scheduling has been known as an effective technique for increasing the system capacity of orthogonal frequency-division multiple-access (OFDMA) systems. By increasing the channels' frequency selectivity with different cyclic delays applied on transmit antennas, the merit of multiuser diversity can be more effectively exploited in the system. In this paper, we aim to optimize the design of the CDD-aided frequency-selective scheduling for OFDMA downlink systems. Optimization is done from two aspects: cyclic-delay search and scheduling-information feedback. In the optimization of cyclic-delay search, three new methods are proposed, including antenna-wise sequential search for frequency-nonselective (AWSS-FNS) channels, AWSS for frequency-selective (AWSS-FS) channels, and a genetic-algorithm-based search (GAS). AWSS-FNS achieves the optimal performance if a channel is frequency nonselective over a subchannel, whereas AWSS-FS and GAS provide good tradeoffs between system performance and complexity for channels that are frequency selective over a subchannel. In the optimization of scheduling-information feedback, a new channel-dependent feedback (CDF) method is proposed, where the feedback resource is allocated to users according to their frequency-selectivity rates and a principle of proportional fairness. The optimized scheduler is shown to provide significant improvement in both system sum rate and user fairness over previous methods under fixed feedback overhead.**

***Index Terms*—Cyclic-delay diversity (CDD), frequency-selective scheduling, orthogonal frequency-division multiple access (OFDMA).**

I. Introduction

ORTHOGONAL frequency-division multiplexing (OFDM) is an effective modulation/multiplexing scheme for combatting intersymbol interference (ISI) incurred in high-data-rate transmissions [1]. By using orthogonal subcarriers along with a cyclic prefix, ISI can be removed completely as long as the cyclic prefix is larger than the maximum delay spread of the channel. Orthogonal frequency-division multiple access (OFDMA), which is an OFDM-based multiple-access technique where users use different sets of subcarriers (subchannels) for communications, 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 Third-Generation Partnership Project Long-Term Evolution downlink [2] and the IEEE 802.16e specification [3].

Cyclic-delay diversity (CDD) is a simple transmit diversity technique in which different cyclic delays are applied to antennas to create frequency selectivity in the channel, hence increasing 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 [4]–[19]. In particular, CDD has been employed along with channel coding to improve link performance [4]–[11] and along with frequency-selective scheduling to increase the system capacity of OFDMA systems [12]–[19]. For the latter, in [12]–[14], a frequency-selective scheduling based on single-degree CDD (SD-CDD) was proposed for OFDMA downlink systems, where only one cyclic-delay set is used for all subchannels by a user. In [15] and [16], a scheme called multidegree CDD (MD-CDD) was proposed to improve the performance of SD-CDD, where from a book of cyclic-delay sets, a user can select the best one for a particular subchannel. In [15], the design of the book of cyclic-delay sets is randomly generated and thus called multidegree random CDD (MD-RCDD), whereas in [16], MD-RCDD was improved by using an adaptive method for the design of the book and was named multidegree adaptive CDD (MD-ACDD). In [17], an exhaustive search (ES) of the optimal cyclic-delay set that maximizes subchannel sum rate was proposed; although the method can optimize subchannel sum rate, its computational complexity exponentially increases with the number of transmit antennas and/or the size of cyclic-delay sets.

In this paper, we aim to optimize the design of the CDD-aided frequency-selective scheduling for OFDMA downlink systems. Optimization has been done from two aspects: cyclic-delay search and scheduling-information feedback. Three low-complexity methods are proposed in search of cyclic delays, including antenna-wise sequential search for frequency-nonselective (AWSS-FNS) channels, AWSS for frequency-selective (AWSS-FS) channels, and a genetic-algorithm-based search (GAS). AWSS-FNS is optimal if a channel is frequency nonselective over the subchannel bandwidth, whereas GAS and AWSS-FS, first proposed in [18] and [19], respectively, provide

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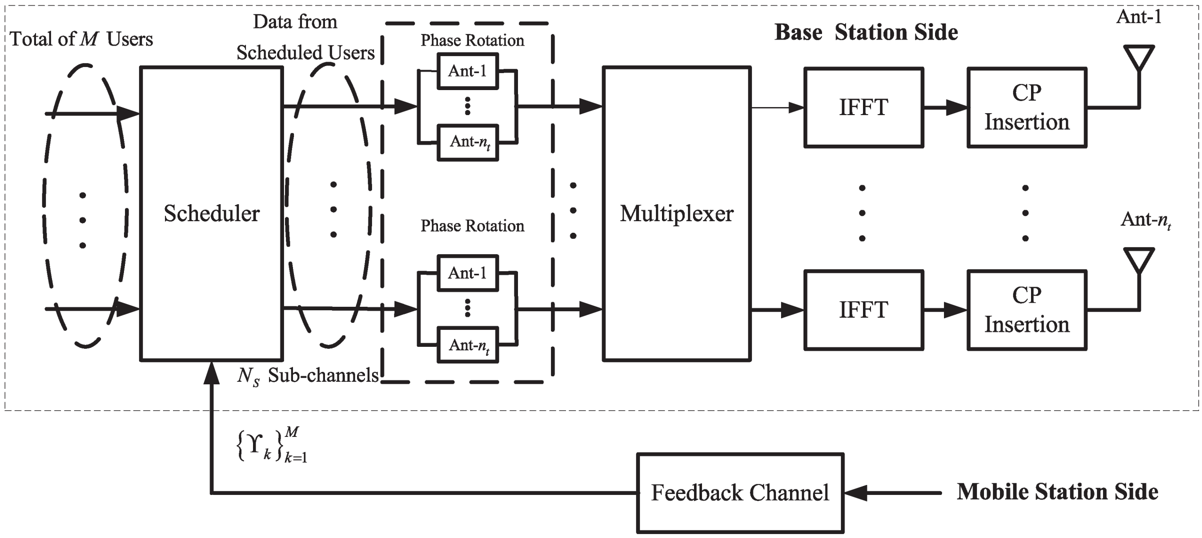

Fig. 1. Comparisons of cyclic-delay search methods under different frequency-selectivity rates.

good tradeoffs between system performance and complexity for a channel that is frequency selective over the subchannel bandwidth. In the scheduling-information feedback, the total feedback overhead is allocated to users according to their frequency-selectivity rates and a principle of proportional fairness to optimize the system performance. Extensive computer simulations show that, under fixed feedback overhead, the optimized scheduler provides significant improvement in both system sum rate and user fairness over MD-ACDD. Compared with [18] and [19], the major new contributions of this paper are inclusions of AWSS-FNS (see Section III-A), an investigation on the total number of subchannel reporting (see Section IV-A), a channel-dependent feedback (CDF) method (see Section IV-B), and an investigation on the effect of nonperfect channel estimation (see Section V).

The remainder of this paper is organized as follows. Section II describes the system and channel models. Section III gives the proposed methods in search of optimal cyclic delays and an analysis on the computational complexity. Section IV presents the proposed CDF method. Numerical results and conclusions are given in Sections V and VI, respectively.

II. System and Channel Models

A. System Model

We consider an OFDMA downlink system with M users. The frequency band of the system consists of N_{FFT} subcarriers and is divided into N_S subchannels with $N_C = N_{\mathrm{FFT}}/N_S$ adjacent subcarriers in each subchannel (adjacent subcarrier allocation). The base station (BS) is equipped with n_t transmit antennas, and each mobile station (MS) is equipped with n_r receive antennas. In the application of the CDD-aided frequency-dependent scheduling, the antennas at the BS are used to create varied channel responses among users by applying different sets of cyclic delays on the antennas so that the merit of multiuser diversity can be exploited at the level of small-scale fading. The antennas at the MSs, on the other hand, are used for receive diversity to improve the link performance. For notation simplicity, only $n_r = 1$ is treated explicitly in Sections II–IV, with the results on $n_r = 2$ being presented in Section V.

It is worth mentioning that frequency-selective scheduling is mainly applied to users with adjacent subcarrier allocation because, in the distributed subcarrier allocation, the best cyclic delay set has to be searched for each subcarrier and reported to the BS; the complexity will become formidable in real implementation [13]–[17].

Fig. 1 is the system architecture. At the MS side, each user, e.g., MS k, finds the best set of cyclic delays along with the subchannel sum rate for each of all subchannels (a cyclic-delay for a transmit antenna) using the proposed methods in Section III. Denote $\{\hat{\Delta}^i_{p\to k}\}_{i=1}^{n_t}$ and $\hat{C}_{p\to k}$ as the best set of cyclic delays and the corresponding sum rate (in bps/Hz) for subchannel p, respectively, where $\hat{\Delta}^i_{p\to k}$ is the best cyclic delay for transmit antenna i.[1] Then, each user, e.g., MS k, reports to the BS a list of two-tuples $\Upsilon_k = \{(\{\hat{\Delta}^i_{p\to k}\}_{i=1}^{n_t}, \hat{C}_{p\to k})\}$ that corresponds to subchannels with the $|\Upsilon_k|$ largest sum rates, where $|\Upsilon_k|$ is the cardinality of Υ_k. In other words, $|\Upsilon_k|$ is the number of subchannels to be reported by MS k, which is determined by the BS using the proposed method of CDF in Section IV. In practice, $|\Upsilon_k|$ is different from one user to another and is often much smaller than N_S due to the limitation on the feedback overhead. In addition, a particular subchannel may be reported by more than one user, but it is up to the scheduler at the BS to decide to whom this particular subchannel is to be allocated. Theoretically, the reporting of the best set of cyclic delays and capacity should be done for each subcarrier rather than for each subchannel to achieve the best system performance. In practice, however, this is not possible because of the feedback-overhead limitation.

At the BS side, the scheduler carries out the allocation of subchannels to users based on the feedback information $\{\Upsilon_k\}_{k=1}^{M}$ provided by all users. After scheduling, as in Fig. 1, the data from the scheduled users are cyclically delayed (performed in

[1] Without loss of generality, $\hat{\Delta}^1_{p\to k}$ will be set to zero in this paper.

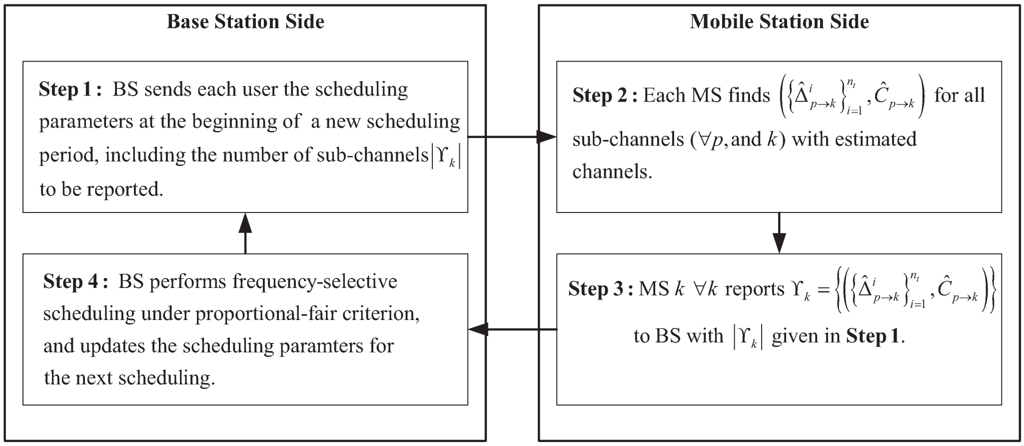

Fig. 2. System operational procedure (no segmentation in a subchannel).

the frequency domain) and OFDM-modulated before passed to antennas for transmission. The number of scheduled users per scheduling period is often smaller than the total number of users M.

B. Scheduler

In a frequency-selective scheduling, the improvement on system performance mainly comes from the scheduler at the BS that exploits the advantage of multiuser diversity based on the information feedback from all users, i.e., $\{\Upsilon_k\}_{k=1}^{M}$. Since proportional-fairness scheduling has been well known for its ability to provide a good balance between system capacity and user fairness [25]–[27], the one proposed in [27] is employed in this paper, where subchannel p will be scheduled to MS k if

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

where $r_{p\to j} = \hat{C}_{p\to j} B_S$ is the achievable rate if subchannel p is scheduled to MS j, $B_S = N_C \cdot 1/(N_{\mathrm{FFT}} T_s)$ is the bandwidth of subchannel, T_s is the sampling time of OFDM signals, $\hat{C}_{p\to j}$ is the subchannel sum rate achieved using $\{\hat{\Delta}^i_{p\to k}\}_{i=1}^{n_t}$, 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, i.e., $I(j) = 1$ if MS j is scheduled, and $I(j) = 0$ otherwise, and Ω_j be the set of subchannels scheduled to MS j. Then, R_j is updated using the following exponential moving average on the short-term data $\{I(j)\sum_{p\in\Omega_j} r_{p\to j}\}$:

$$Rj \leftarrow \frac{(W-1)Rj + I(j)\sum\limits_{p\in\Omega_j} r_{p\to j}}{W} \tag{2}$$

where W is a time constant that controls how fast the old data are being forgotten. Note that, if subchannel p is not reported by a user, then it is not available for scheduling to that user. In addition, if subchannel p has been scheduled to a user, it is no longer available to other users.

For clarity, the system operational procedure is summarized as in Fig. 2 (assuming no segmentation in a subchannel for simplicity, see Section IV). First, at the beginning of a scheduling period, the BS sends the scheduling parameters to each of the M users, including the number of subchannels $|\Upsilon_k|$ to be reported. Second,, each user, e.g., MS k, finds $(\{\hat{\Delta}^i_{p\to k}\}_{i=1}^{n_t}, \hat{C}_{p\to k})$ for all subchannels ($\forall\, p$) using an estimated channel. Third, every user reports $\Upsilon_k = \{(\{\hat{\Delta}^i_{p\to k}\}_{i=1}^{n_t}, \hat{C}_{p\to k})\}$ to the BS with $|\Upsilon_k|$ given in the first step. Finally, the scheduler at the BS carries out the schedule following the proportional fairness rule given in (1) and (2), and updates the scheduling parameters according to the method of CDF in Section IV for the next scheduling.

C. Signal and Channel Model

Consider the signal destined to MS k that is assumed to use all subchannels for notation simplicity. (In real OFDMA systems, subchannels are shared by the scheduled users, and data from those users are multiplexed together before being passed to inverse fast Fourier transform (IFFT), as shown in Fig. 1.) Let $S_k(m)$, $m = 0, \ldots, N_{\mathrm{FFT}} - 1$, be the data symbols and $\hat{\Delta}_i$ be the cyclic delay for antenna i. Using CDD, the transmitted OFDM signal from antenna i is expressed by

$$s_i(n) = \frac{1}{\sqrt{N_{\mathrm{FFT}}}} \sum_{m=0}^{N_{\mathrm{FFT}}-1} e^{-j\left(\frac{2\pi m \hat{\Delta}_i}{N_{\mathrm{FFT}}} + \psi_i(m)\right)} S_k(m) e^{j\frac{2\pi m n}{N_{\mathrm{FFT}}}}$$
$$n = -N_g, \ldots, N_{\mathrm{FFT}} - 1 \tag{3}$$

where $((2\pi m\hat{\Delta}_i)/N_{\mathrm{FFT}})$ is the phase rotation used to implement the cyclic delay in the frequency domain, $\psi_i(m)$ is a subcarrier correction term to improve performance, as will be discussed in Section III, N_g is the length of the cyclic prefix, and $j = \sqrt{-1}$. In (3), the values of $\hat{\Delta}_i$ are integers and limited to the values of $0, \ldots, N_{\mathrm{FFT}} - 1$.

The channel from antenna i to user k is modeled by the impulse response $h_{i\to k}(\tau) = g_k \sum_{l=0}^{L_k} h_{i\to k}(l)\delta(\tau - lT_s)$, where g_k denotes the propagation loss due to path loss and shadowing, $\{h_{i\to k}(l)\}_{l=0}^{L_k}$ are the tap gains modeling the small-scale fading of the channel that is assumed time-invariant during the scheduling period (low-mobility users), and $L_k + 1 \leq N_g$ is the length of the channel. For Rayleigh fading considered here, $\{h_{i\to k}(l)\}_{l=0}^{L_k}$ are mutually independent complex Gaussian random variables with zero mean and variance $\sigma_{k,l}^2$.

In particular, the exponential multipath intensity profile is adopted with $\sigma_{k,l}^2 = \sigma_{k,0}^2 \cdot \exp(-lT_s/T_{\mathrm{RMS},k})$, where $T_{\mathrm{RMS},k}$ is the RMS delay spread, and $\sigma_{k,0}^2$ is set to be $\sigma_{k,0}^2 = (1 - \exp(-T_s/T_{\mathrm{RMS},k}))$ to have $\sum_{l=0}^{L_k} \sigma_{k,l}^2 = 1$. Furthermore, the channels are independent and identically distributed (i.i.d.) between different antennas of the same user, and are independent among different users.

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

$$Y_k(m) = g_k H_k(m) S_k(m) + N_k(m) \qquad m = 0, \ldots, N_{\mathrm{FFT}} - 1 \quad (4)$$

where

$$H_k(m) = \frac{1}{\sqrt{n_t}} \sum_{i=1}^{n_t} e^{-j\left(\frac{2\pi m \hat{\Delta}_i}{N_{\mathrm{FFT}}} + \psi_i(m)\right)} H_{i\to k}(m) \quad (5)$$

$$H_{i\to k}(m) = \sum_{n=0}^{N_{\mathrm{FFT}}-1} h_{i\to k}(n) e^{-j\frac{2\pi m n}{N_{\mathrm{FFT}}}} \quad (6)$$

$\{N_k(m)\}$ are i.i.d. Gaussian variables with zero mean and variance $\sigma_N^2 = E[|N_k(m)|^2]$, $E[\cdot]$ denotes the operation of taking expectation, and $h_{i\to k}(n) = 0, n = L_k + 1, \ldots, N_{\mathrm{FFT}} - 1$. Note that the use of a cyclic delay in (5) is to increase channel selectivity so that the merit of multiuser diversity can be exploited more effectively. In practice, the channel response $\{h_{i\to k}(l)\}_{l=0}^{L_k}$ has to be estimated by each user for all $i = 1, \ldots, n_t$; the effects of nonperfect channel estimation will be investigated in Section V.

III. Optimization of Cyclic-Delay Search

The sum rate of a subchannel will be used as the performance index in the search of the best set of cyclic delays for that subchannel. For MS k, the sum rate of subchannel p is given by

$$C_{p\to k} = \sum_{m=(p-1)N_C}^{pN_C-1} \log_2\left(1 + g_k^2 |H_k(m)|^2 \cdot \sigma_S^2/\sigma_N^2\right) \text{ bps/Hz} \qquad 1 \le p \le N_S \quad (7)$$

where $H_k(m)$ is evaluated in (5) and (6) with $\hat{\Delta}_i$ replaced by $\hat{\Delta}_{p\to k}^i$, $i = 1, \ldots, n_t$, and $\sigma_S^2 = E[|S_k|^2]$ is the average power of the data symbol. The optimal set of cyclic delays is the one that maximizes $C_{p\to k}$, i.e.,

$$\left\{\hat{\Delta}_{p\to k}^i\right\}_{i=1}^{n_t} = \arg\left\{\max_{\substack{\left\{\Delta_{p\to k}^i\right\}_{i=1}^{n_t}, \\ \Delta_{p\to k}^1 = 0}} C_{p\to k}\right\}. \quad (8)$$

In practice, $\Delta_{p\to k}^i$ and $C_{p\to k}(\{\hat{\Delta}_{p\to k}^i\}_{i=1}^{n_t})$ need to be quantized before being reported to the BS due to limitation on the feedback overhead. Define $\Lambda \doteq \{Q_\Delta[\Delta_{p\to k}^i]\}$, $i = 1, \ldots, n_t$, and $\Xi \doteq \{Q_C[C_{p\to k}]\}$ as the sets of quantized cyclic delays and sum rates, respectively, where $Q_\Delta[\cdot]$ and $Q_C[\cdot]$ denote the operations of quantization for reducing the feedback overhead. Λ and Ξ will be assumed the same for all p, k, and i. In addition, $|\Lambda| = 2^{b_\Delta}$, and $|\Xi| = 2^{b_C}$, where b_Δ and b_C are the feedback bit numbers for reporting a cyclic delay and a subchannel sum rate, respectively.

Taking into consideration the quantization effects, the optimization in (8) becomes

$$\left\{\hat{\Delta}_{p\to k}^i\right\}_{i=1}^{n_t} = \arg\left\{\max_{\substack{\left\{\Delta_{p\to k}^i\right\}_{i=1}^{n_t} \in \Lambda^{n_t}, \\ \Delta_{p\to k}^1 = 0}} \{C_{p\to k}\}\right\} \quad (9)$$

where Λ^{n_t} is the n_t-fold Cartesian product of Λ. Using $\{\hat{\Delta}_{p\to k}^i\}_{i=1}^{n_t}$, the quantized subchannel sum rate is obtained by $\hat{C}_{p\to k} \doteq Q_C[C_{p\to k}(\{\hat{\Delta}_{p\to k}^i\}_{i=1}^{n_t})] \in \Xi$. After $(\{\hat{\Delta}_{p\to k}^i\}_{i=1}^{n_t}, \hat{C}_{p\to k})$ is found for each subchannel, the list of two-tuples $\Upsilon_k = \{(\{\hat{\Delta}_{p\to k}^i\}_{i=1}^{n_t}, \hat{C}_{p\to k})\}$ [2] that corresponds to subchannels with the $|\Upsilon_k|$ largest capacities will be reported to the BS for scheduling.

Here, three new methods are proposed to optimize the search of cyclic delays under different channel conditions.

A. Frequency-Nonselective Over Subchannel Bandwidth

For the case where subchannel bandwidth B_S is less than the channel's coherent bandwidth $(\Delta f)_{c,k}$, the subcarrier response $H_{i\to k}(m)$ in (6) is the same for all m in the subchannel. Therefore, the set of cyclic delays optimized for a subcarrier can be applied to other subcarriers after a phase correction denoted by $\psi_i(m)$ in (5). A low-complexity algorithm, i.e., AWSS-FNS, is proposed for this case. As to be shown, AWSS-FNS achieves the best performance if the quantization effect is neglected. In the following, the subcarrier used for the cyclic-delay search will be indexed by $\bar{m}$, where $(p-1)N_C \le \bar{m} \le pN_C - 1$ for subchannel p.

The basic idea of AWSS-FNS is that the optimal cyclic delay of an antenna is searched one after another, given the cyclic delays obtained for previous antennas. In particular, starting from $i = 2$, the optimal cyclic delay $\hat{\Delta}_{p\to k}^i$ is obtained by

$$\hat{\Delta}_{p\to k}^i(\bar{m}) = \arg\left\{\max_{\Delta_{p\to k}^i} C_{p\to k}^i(\bar{m})\right\}, \quad i = 2, \ldots, n_t \quad (10)$$

where

$$C_{p\to k}^i(\bar{m}) = \log_2\left(1 + g_k^2 \left|\left(H_{k,\,i-1}(\bar{m}) + e^{-j\frac{2\pi\bar{m}\hat{\Delta}_{p\to k}^i(\bar{m})}{N_{\mathrm{FFT}}}} \times H_{i\to k}(\bar{m})\right)\right|^2 \cdot \frac{\sigma_S^2}{\sigma_N^2}\right) \quad (11)$$

$$H_{k,\,i-1}(\bar{m}) = \sum_{l=1}^{i-1} e^{-j\left(\frac{2\pi\bar{m}\hat{\Delta}_{p\to k}^l(\bar{m})}{N_{\mathrm{FFT}}}\right)} H_{l\to k}(\bar{m}). \quad (12)$$

[2]As to be discussed in Section IV, an estimated frequency-selective rate may be also reported if segmentation is considered in a subchannel.

TABLE I
AWSS-FNS ALGORITHM

Input: $H_{i\to k}(\bar{m}),\ i{=}1,\cdots,n_t;\ \bar{m};\ \Lambda;\ \Xi$
Output: $\left\{\hat{\Delta}^i_{p\to k}(\bar{m})\right\}_{i=2}^{n_t};\ \hat{C}_{p\to k}$

1. $\hat{\Delta}^1_{p\to k}(\bar{m}){=}0;\ H_{i\to k}(m){=}H_{i\to k}(\bar{m}),\ (p-1)N_C \le m \le pN_C-1$
2. for $i{=}2$ to n_t do
3. $H_{k,i-1}(\bar{m}){=}\sum_{l=1}^{i-1} e^{-j\left(\frac{2\pi\bar{m}\hat{\Delta}^l_{p\to k}(\bar{m})}{N_{\mathrm{FFT}}}\right)} H_{l\to k}(\bar{m})$
4. $\hat{\Delta}^i_{p\to k}(\bar{m}){=}Q_\Delta\left[\frac{N_{\mathrm{FFT}}}{2\pi\bar{m}}\left[\left(\angle H_{k,i-1}(\bar{m})-\angle H_{i\to k}(\bar{m})\right)+2\pi n\right]\right]$
5. $\psi_i(m){=}\frac{2\pi(\bar{m}-m)\hat{\Delta}^i_{p\to k}(\bar{m})}{N_{\mathrm{FFT}}}$
6. end for
7. $\hat{C}_{p\to k}(m){=}$
$\log_2\left(1{+}g_k^2\left|\frac{1}{\sqrt{n_t}}\sum_{i=1}^{n_t} e^{-j\left(\frac{2\pi m\hat{\Delta}^i_{p\to k}(\bar{m})}{N_{\mathrm{FFT}}}+\psi_i(m)\right)} H_{i\to k}(m)\right|^2\cdot\frac{\sigma_S^2}{\sigma_N^2}\right)$
8. $\hat{C}_{p\to k}{=}Q_C\left[\sum_{m=(p-1)N_C}^{pN_C-1}\hat{C}_{p\to k}(m)\right]$

In (11), $H_{i\to k}(\bar{m})$ is the same for $(p-1)N_C \le \bar{m} \le pN_C - 1$, and without loss of generality, we set $\psi_i(\bar{m}) = 0$. Let $H_{k,i-1}(\bar{m}) = |H_{k,i-1}(\bar{m})|e^{j\angle H_{k,i-1}(\bar{m})}$ and $H_{i\to k}(\bar{m}) = |H_{i\to k}(\bar{m})|e^{j\angle H_{i\to k}(\bar{m})}$. It is clear that $\hat{\Delta}^i_{p\to k}(\bar{m})$ is given by

$$\hat{\Delta}^i_{p\to k}(\bar{m}) = \frac{N_{\mathrm{FFT}}}{2\pi\bar{m}}\left[\left(\angle H_{k,i-1}(\bar{m}) - \angle H_{i\to k}(\bar{m})\right) + 2\pi n\right] \tag{13}$$

where n is an integer to make $0 \le \hat{\Delta}^i_{p\to k}(\bar{m}) < N_{\mathrm{FFT}}$. In other words, with this choice of the cyclic delay, both addends in (11) have the same phase that maximizes the sum rate. After finding $\hat{\Delta}^i_{p\to k}(\bar{m})$, the phase correction term $\psi_i(m)$ for subcarrier m in the subchannel is given by

$$\psi_i(m) = \frac{2\pi(\bar{m} - m)\hat{\Delta}^i_{p\to k}(\bar{m})}{N_{\mathrm{FFT}}} \tag{14}$$

which is applied to ensure that all subcarriers have the same phase rotation of $((2\pi\bar{m}\hat{\Delta}^i_{p\to k}(\bar{m}))/N_{\mathrm{FFT}})$. From (13) and (14), the use of $\hat{\Delta}^i_{p\to k}(\bar{m})$ and $\psi_i(m)$ achieves the subchannel sum-rate upper bound, as shown in the following:

$$\begin{aligned} C_{p\to k} &= \sum_{m=(p-1)N_C}^{pN_C-1} \log_2\left(1+g_k^2\left|\frac{1}{\sqrt{n_t}}\sum_{i=1}^{n_t} e^{-j\left(\frac{2\pi m\hat{\Delta}^i_{p\to k}(\bar{m})}{N_{\mathrm{FFT}}}+\psi_i(m)\right)}\right.\right. \\ &\qquad\qquad \left.\left.\times H_{i\to k}(m)\right|^2\cdot\frac{\sigma_S^2}{\sigma_N^2}\right) \\ &\le \sum_{m=(p-1)N_C}^{pN_C-1} \log_2\left(1 + \frac{g_k^2}{n_t}\left|\sum_{i=1}^{n_t}|H_{i\to k}(m)|\right|^2\cdot\frac{\sigma_S^2}{\sigma_N^2}\right) \\ &\doteq \hat{C}^{\mathrm{bound}}_{p\to k}. \end{aligned} \tag{15}$$

Therefore, the proposed AWSS-FNS is optimal in the search of cyclic delays that maximize the subchannel sum rate. In practice, $\hat{\Delta}^i_{p\to k}(\bar{m})$ and $\hat{C}_{p\to k}$ have to be quantized before being reported to the BS. Taking into consideration the effect of quantization, the proposed AWSE-FNS is given in Table I.

B. Frequency-Selective Over Subchannel Bandwidth

For the case where subchannel bandwidth B_S is larger than the channel's coherent bandwidth $(\Delta f)_{c,k}$, AWSS-FNS is no longer optimal because $H_{i\to k}(m) \ne H_{i\to k}(n)$ for $m \ne n$ in a subchannel. In this case, as is shown in (7)–(9), $C_{p\to k}$ is a highly nonlinear function of $\{\{\Delta^i_{p\to k}\}_{i=1}^{n_t} \in \Lambda^{n_t}\}$, and (7) cannot be solved in an analytical way. Theoretically, $\{\hat{\Delta}^i_{p\to k}\}_{i=1}^{n_t}$ can be found through ES; however, its complexity increases exponentially with n_t and/or $|\Lambda|$. Here, two algorithms, namely, GAS and AWSS-FS, are proposed for efficient search of the best set of cyclic delays. The proposed methods provide good tradeoffs between performance and complexity, as will be shown in Section V.

1) GA-Based Search: The GA is an evolutionary algorithm proposed by Holland in 1960s [21] and has been widely recognized as a powerful technique to find solutions for a wide range of optimization and search problems [21]–[24]. The operation of the GA is shown in Fig. 3, where the parameters of the objective function are encoded as genes and a set of genes as a chromosome, which is a candidate solution to the objective function. Initially, the GA is started with an initial population of chromosomes, and each chromosome is evaluated against the objective function. Then, a *survivor selection* is applied to select better-fit chromosomes for evolution if the best one is regarded as unsatisfactory. The evolution operations include *mate selection*, *crossover,* and *mutation*. The *mate selection*

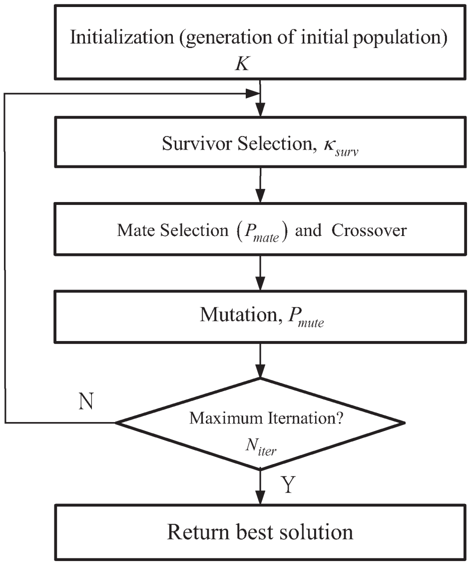

Fig. 3. Operation of GAs.

picks chromosome mates (parents) from the survivors, and *crossover* (recombination) is then carried out over the selected mates to reproduce a new offspring that inherits parts of its genes from its parents. *Mutation* is an operation to produce a few offspring whose genes may be altered, aiming to force the GA to explore other areas of the solution space to avoid falling into a local optimum. Finally, the process repeats from one generation to another until the termination condition (for example the number of iterations) is met.

The GA has been successfully applied to a wide range of optimization problems that involve a large number of variables [21]–[24]. For the case of a frequency-selective subchannel, the GA-based approach is particularly useful when the number of subcarriers and/or the number of antennas are large, where the optimization based on ES is prohibitive.

A specific GA is devised here to solve the optimization problem in (9). The details of the algorithm are given below with subchannel p regarded as to be scheduled to MS k.

- *Definition of gene and chromosome*. The quantized cyclic delay $\Delta^i_{p\to k} \in \Lambda$ of each transmit antenna is encoded as a gene, and the set of genes $\{\Delta^i_{p\to k}\}_{i=1}^{n_t} \in \Lambda^{n_t}$ is encoded as a chromosome, which is a feasible solution to the optimization problem in (9).
- *Objective function.* Subchannel sum rate $C_{p\to k}$ in (7) is employed as the objective function in search of the best set of cyclic delays.
- *Initial population.* A mixture of random and deterministic chromosomes is employed to constitute the initial population. The use of deterministic chromosomes is to accelerate the GA convergence, as will be shown in Section V. In particular, the initial population of size K is divided into two subsets: one is generated at random, and the other is deterministic. The deterministic set consists of the set of cyclic delays each being the optimal one for a particular subcarrier in subchannel p. Therefore, the deterministic part of the initial population is fixed to the size of N_C. The selection of the deterministic set is given in the Appendix.
- *Survivor selection*. Among the population, the best $\kappa_{\text{surv}}K$ chromosomes will survive and be put into the mating pool for mate selection, where $0 \leq \kappa_{\text{surv}} \leq 1$ and $\kappa_{\text{surv}}K$ is an integer. In this way, the convergence rate of the GA will be increased [21]–[24].
- *Mate selection*. In this process, two chromosomes (mates) are selected from the mating pool by using a roulette-wheel selection [21]–[24] in which chromosome j with fitness value C_j will be selected with the probability $P_{\text{mate},j}$

$$P_{\text{mate},j} = \frac{C_j}{\sum_{m=1}^{\kappa_{\text{surv}}K} C_m}, \qquad j = 1, \ldots, \kappa_{\text{surv}}K. \tag{16}$$

- *Crossover.* After the mates (called parents) are selected, crossover is performed to produce a new offspring whose gene has an equal probability to inherit from its father or mother. Once the new offspring is produced, the mate selection and crossover will be repeated to produce another new offspring until the total number chromosomes is equal to the population size K.
- *Mutation.* A probability P_{mut} is given to each gene of the new offspring to decide whether the gene is mutated or not. If a gene is decided to mutate, then a quantized cyclic delay will be generated randomly as the new gene.
- The procedure of survivor selection to mutation will be repeated until the maximum number of iterations N_{iter} is reached.

The selection of the parameters K, κ_{surv}, and P_{mut} in the proposed GA was discussed in [18].

2) Antenna-Wise Sequential Search for Frequency Selective: The method of AWSS-FS is proposed to lower the complexity of GAS particularly for cases with a small-to-medium number of antennas and/or b_Δ (see Table III). The idea is that the best cyclic delay of an antenna is searched with an ES, given the best cyclic delays obtained previously. As a result, the complexity is proportional to $|\Lambda| \cdot (n_t - 1)$ rather than $|\Lambda|^{(n_t-1)}$ as in the pure ES method. In particular, starting from $i = 2$, the optimal cyclic delay $\hat{\Delta}^i_{p\to k}$ for subchannel p is obtained by

$$\hat{\Delta}^i_{p\to k} = \arg\left\{\max_{\Delta^i_{p\to k}\in\Lambda} C^i_{p\to k}\right\}, \qquad i = 2, \ldots, n_t \tag{17}$$

where

$$C^i_{p\to k} = \sum_{m=(p-1)N_C}^{pN_C-1} \log_2\left(1+g_k^2\left|\left(H_{k,i-1}(m)+e^{-j\frac{2\pi m\Delta^i_{p\to k}}{N_{\text{FFT}}}+\psi_{\Delta^i_{p\to k}}(m)} \times H_{i\to k}(m)\right)\right|^2 \cdot \frac{\sigma_S^2}{\sigma_N^2}\right) \tag{18}$$

$$H_{k,i-1}(m) = \sum_{l=1}^{i-1} e^{-j\left(\frac{2\pi m\hat{\Delta}^l_{p\to k}}{N_{\text{FFT}}}+\psi_l(m)\right)} H_{l\to k}(m) \tag{19}$$

TABLE II
AWSS-FS ALGORITHM

Input: $H_{i\to k}(m),\ i{=}1,\cdots,n_t,\ m{=}(p{-}1)N_C,\cdots,pN_C{-}1;\ \bar{m};\ \Lambda;\ \Xi$
Output: $\left\{\hat{\Delta}^i_{p\to k}\right\}_{i=2}^{n_t};\ \hat{C}_{p\to k}$

1. $H_{k,1}(m){=}H_{1\to k}(m),\ m{=}(p{-}1)N_C,\cdots,pN_C{-}1$
2. for $i{=}2$ to n_t do
3. for $j{=}1$ to $|\Lambda|$ do
4. $C^j_{\mathrm{temp}}{=}0$
5. for $m{=}(p{-}1)N_C$ to $m{=}pN_C{-}1$ do
6. $\psi_{\Delta_j}(m){=}\frac{2\pi(\bar{m}-m)\Delta_j}{N_{\mathrm{FFT}}},\ \Delta_j{\in}\Lambda$
7. $C^j_{\mathrm{temp}}{=}C^j_{\mathrm{temp}}{+}$ $\log_2\left(1{+}g_k^2\left|\left(H_{k,i-1}(m){+}e^{-j\left(\frac{2\pi m\Delta_j}{N_{\mathrm{FFT}}}+\psi_{\Delta_j}(m)\right)}H_{i\to k}(m)\right)\right|^2\cdot\frac{\sigma_S^2}{\sigma_N^2}\right)$
8. end for
9. end for
10. $q{=}\arg\left\{\max\limits_j C^j_{\mathrm{temp}}\right\}$
11. $\hat{\Delta}^i_{p\to k}{=}\Delta_q;\ C^i_{p\to k}{=}C^q_{\mathrm{temp}}$
12. for $m{=}(p{-}1)N_C$ to $pN_C{-}1$ do
13. $\psi_i(m){=}\frac{2\pi(\bar{m}-m)\hat{\Delta}^i_{p\to k}}{N_{\mathrm{FFT}}}$
14. $H_{k,i}(m){=}H_{k,i-1}(m){+}e^{-j\left(\frac{2\pi m\hat{\Delta}^i_{p\to k}}{N_{\mathrm{FFT}}}+\psi_i(m)\right)}H_{i\to k}(m)$
15. end for
16. end for
17. $\hat{C}_{p\to k}{=}Q_C\left[C^{n_t}_{p\to k}\right]$

where $\psi_{\Delta^i_{p\to k}}(m)$ is given by (14) with $\hat{\Delta}^i_{p\to k}$ replaced by $\Delta^i_{p\to k}$. The detail of the algorithm is summarized in Table II.

Complexity Analysis: The computational complexity of searching the best set of cyclic delays per subchannel for the proposed GAS and AWSS-FS algorithms is summarized in Table III, including the number of real multiplications and additions. The complexity of a pure ES and MD-ACDD are also analyzed for comparison purposes. For the ES, the complexity of searching a set of cyclic delays is calculated by counting the additions and multiplications needed in (7). Since there are a total of $|\Lambda|^{(n_t-1)}$ sets of cyclic delays to be evaluated, the total complexity is $|\Lambda|^{(n_t-1)}$ times the complexity of one cyclic-delay set. For AWSS-FS, the complexity per antenna is evaluated by counting the additions and multiplications needed in (18) and (19), and the total complexity is (n_t-1) times the complexity per antenna. For GAS, the complexity consists of the complexity of initialization and that incurred within the search loop in Fig. 3. The latter is evaluated by calculating the complexity per iteration, and the total complexity is N_{iter} times the complexity per iteration. The complexity per iteration is evaluated by counting the number of additions and multiplications needed in (7), which is calculated K times per iteration. In MD-ACDD, each MS finds a set of cyclic delays for each of the subchannels from a book of cyclic-delay sets, aiming to maximize the sum rate of the center subcarrier. The size of the book is given by Z.

IV. Optimization of Scheduling-Information Feedback

As discussed in Section II-B, $\Upsilon_k=\{(\{\hat{\Delta}^i_{p\to k}\}_{i=1}^{n_t},\hat{C}_{p\to k})\}$ have to be reported by MS k in order for the scheduler at the BS to work properly. Here, the design of feedback of Υ_k is optimized. First, the total number of subchannel reporting is designed to ensure that each subchannel is reported by at least an MS with high probability; if this is not the case, the unreported subchannels would be assigned to MSs on a random basis, and that will degrade the system performance very significantly, as shown in Section V. Second, a new CDF method is proposed, where the feedback resource is allocated to users according to user's channel selectivity and a principle of proportional fairness.

A. Total Number of Subchannel Reporting

Let $N_{S,k}$ be the number of subchannel reporting allocated to MS k. Theoretically, if every subchannel is reported by each MS, the scheduler would have complete information for scheduling and thus the best performance; the feedback overhead, however, will be too large to be realized in practical systems. In this paper, the total number of subchannel reporting by all users is fixed at $N_{r,\mathrm{total}}=\sum_{k=1}^{M}N_{S,k}\doteq N_S\cdot\mu_M$, where $0<\mu_M\leq M$ is the subchannel reporting factor that is

TABLE III
COMPUTATIONAL COMPLEXITY OF DIFFERENT CYCLIC-DELAY SEARCHES

ES [17]		
Number of real additions	Per CD set	$N_C(1+4n_t)-1$
	Total	$\lvert\Lambda\rvert^{(n_t-1)}(N_C(1+4n_t)-1)$
Number of real multiplications	Per CD set	$N_C(5+6n_t)$
	Total	$\lvert\Lambda\rvert^{(n_t-1)}N_C(5+6n_t)$
MD-ACDD [16]		
Number of real additions	Per CD set	$(N_C+4n_tN_C-1)$
	Total	$Z\cdot(N_C+4n_tN_C-1)$
Number of real multiplications	Per CD set	$(5+6n_t)N_C$
	Total	$Z\cdot(5+6n_t)N_C$
AWSS-FS		
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	$(n_t-1)\lvert\Lambda\rvert(9N_C)$
GAS		
Number of real additions	Initialization	$5(n_t-1)N_C$
	Per iteration	$K(N_C+4n_tN_C-1)$
	Total	$N_{\text{iter}}K(N_C+4n_tN_C-1)+$ $5(n_t-1)N_C$
Number of real multiplications	Initialization	$8(n_t-1)N_C$
	Per iteration	$K(5+6n_t)N_C$
	Total	$N_{\text{iter}}K(5+6n_t)N_C+$ $8(n_t-1)N_C$

designed to ensure that each subchannel is reported by at least a MS with high probability.

On the average, the number of subchannel reporting can be assumed to be shared equally by all MSs, i.e., $N_{S,k}=N_S\cdot\mu_M/M$, and each subchannel will be reported with equal probability by an MS. In such a case, the probability of subchannel p being reported by MS k is $P_{p,k}=\binom{N_S-1}{N_{S,k}-1}\Big/\binom{N_S}{N_{S,k}}=\mu_M/M$ for all k. Moreover, the probability that a particular subchannel is reported by at least a MS is given by

$$P_{\text{rep}}=1-\left(1-\frac{\mu_M}{M}\right)^M. \tag{20}$$

P_{rep} can be selected to strike a balance between the system performance and feedback overhead, and given P_{rep}, μ_M and $N_{r,\text{total}}$ can be determined by following (20) and $N_{r,\text{total}}=N_S\cdot\mu_M$. As shown in Section V, $0.98\le P_{\text{rep}}\le 0.99$ often gives a good tradeoff between system performance and feedback overhead.

B. Channel-Dependent Feedback for MSs With Different Frequency-Selectivity Rates

The proposed CDF involves two steps: allocation of subchannel reporting followed by allocation of segment reporting. The basic idea is that the total number of subchannel reporting $N_{r,\text{total}}=N_S\cdot\mu_M$, which is determined by P_{rep} in (20), is allocated first to users in an optimized way. Then, the spare feedback resource is allocated to users with frequency-selectivity

TABLE IV
ALLOCATION OF SUBCHANNEL REPORTING

```
Input: α_j, j=1,···,M; N_{r,total}; N_S
Output: N_{S,j}, j=1,···,M

1.  N_rem=N_{r,total}; S≐{1,···,M}
2.  for n=1 to M do
3.     k=arg{ max_{j∈S} α_j }; N_{S,k}=round(α_k N_{r,total})
4.     if N_{S,k}>min(N_S,N_rem) then
5.        N_{S,k}=min(N_S,N_rem)
6.     end if
7.     N_rem=N_rem−N_{S,k}; S←S\{k}
8.  end for
```

rate larger than 1 for segment reporting in a subchannel to improve performance. The frequency-selectivity rate of MS k is defined as $\gamma_k\doteq B_S/(\Delta f)_{c,k}$, where $(\Delta f)_{c,k}\doteq 1/(5T_{\text{RMS},k})$. Here, γ_k is assumed being estimated accurately at an MS and reported to the BS. The effect of nonperfect estimation will be investigated in Section V.

1) Allocation of Subchannel Reporting: In the proportional-fairness scheduling, it is observed 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-fairness principle. Therefore, in the allocation of subchannel reporting, it would be beneficial if MS k is allowed to report more subchannels than the others. Based on this idea, the ratio of subchannel reporting by MS k is proposed as follows:

$$\alpha_k=\left(\frac{\frac{1}{R_k}}{\sum_{j=1}^M\frac{1}{R_j}}\right)^\beta\Bigg/\sum_{i=1}^M\left(\frac{\frac{1}{R_i}}{\sum_{j=1}^M\frac{1}{R_j}}\right)^\beta \tag{21}$$

where β is a control parameter to control the ratio of reporting among users. A higher β implies that a larger portion of the reporting resource is allocated to users with less data rate, and as β approaches to zero, α_k approaches to $1/M$, which means that all the users have an equal share of the reporting resource. In addition, in (21), $\sum_{k=1}^M\alpha_k=1$, and $\alpha_k=1/M$ if $R_i=R_j,\forall i,j$ and/or $\beta=0$. Using α_k in (21), the best $N_{S,k}=\text{round}(\alpha_kN_{r,\text{total}})\le N_S$ subchannels of MS k will be reported to the BS, where $\text{round}(x)$ is the operation of rounding x to the nearest integer. The detail of the allocation algorithm is given in Table IV, where the pitfall that $\sum_{j=1}^M\text{round}(\alpha_jN_{r,\text{total}})$ may exceed $N_{r,\text{total}}$ is avoided.

2) Allocation of Segment Reporting: In previous works [15]–[19], only one reporting is done for a subchannel no matter the frequency selectivity within the subchannel. Unfortunately, that may limit the system performance, as shown in Section V. A way to combat the channel selectivity within a subchannel is to divide the subchannel into segments of consecutive subcarriers over which the channel is frequency nonselective; then, the optimal set of cyclic delays for segment can be obtained with AWSS-FNS to improve performance.

TABLE V
ALLOCATION OF SEGMENT REPORTING

Input: $N_{r,\text{total}}$; O_{total}; γ_k, $k=1,\cdots,M$
Output: $n_{\text{seg},k}$, $k=1,\cdots,M$

$O_{\text{rem}}=O_{\text{total}}-N_{r,\text{total}}$; $S\doteq\{1,\cdots,M\}$
for $n=1$ to $\max_{k\in S}\text{ceil}(\gamma_k)$ do
  $S_n\leftarrow\{k|k\in S,\text{ceil}(\gamma_k)=n\}$; $O_{\text{seg},S_n}=\sum_{k\in S_n}N_{S,k}(n-1)$
  if $O_{\text{rem}}\geq O_{\text{seg},S_n}$ then
    $n_{\text{seg},k}=n$, $k\in S_n$; $O_{\text{rem}}=O_{\text{rem}}-O_{\text{seg},S_n}$; $S\leftarrow S\backslash S_n$
  else
    if $\text{round}\left(O_{\text{rem}}\Big/\sum_{k\in S_n}N_{S,k}\right)\geq 1$ then
      $n_{\text{seg},k}=\text{round}\left(O_{\text{rem}}\Big/\sum_{k\in S_n}N_{S,k}\right)$, $k\in S_n$
    else
      $n_{\text{seg},k}=1$, $k\in S_n$
    end if
    $S\leftarrow S\backslash S_n$; $n_{\text{seg},k}=1$, $k\in S$; $n=\max_{k\in S}\text{ceil}(\gamma_k)+1$
  end if
end for

Let O_{total} be the total overhead in terms of the number of reporting allowed by the system, i.e.,[3]

$$O_{\text{total}}=\sum_{m=1}^{M}N_{S,k}n_{\text{seg},k} \tag{22}$$

where $n_{\text{seg},k}$ is the number of segment reporting in a subchannel allocated to MS k who has high frequency selectivity. In the proposed method, after the allocation of subchannel reporting, the spare overhead $O_{\text{total}}-N_{r,\text{total}}$ will be allocated to users with high frequency selectivity to report on the segments of subchannels, rather than to report on some other new subchannels.

The allocation of segment reporting is as follows. Starting with the MS(s) having the smallest γ_k to MS(s) having the largest, the number of $n_{\text{seg},k}=\text{ceil}(\gamma_k)$ reports on segments of a subchannel are allocated to MS k if the spare overhead is sufficient for that allocation, where $\text{ceil}(x)$ is the operation to find the minimum integer that is equal to or larger than x. Otherwise, the number of $1\leq n_{\text{seg},k}<\text{ceil}(\gamma_k)$ reporting is allocated. The allocation goes on and on until the spare overhead has been used up. At the MS side, for those MSs with $n_{\text{seg},k}=\text{ceil}(\gamma_k)$, the subchannel is divided into $\text{ceil}(\gamma_k)$ segments over which the channel is frequency nonselective, and AWSS-FNS is applied to obtain the optimal set of cyclic delays. For those MSs with $1\leq n_{\text{seg},k}<\text{ceil}(\gamma_k)$, on the other hand, the subchannel is divided into $1\leq n_{\text{seg},k}<\text{ceil}(\gamma_k)$ segments over which the channel is still frequency selective. In this case, GAS, AWSS-FS or AWSS-NFS can be applied to obtain the set of cyclic delays for segment, depending on a tradeoff between system performance and complexity. The reason why MSs with low γ_k are allocated first is that it is more likely that the segments of those MSs' subchannels are frequency nonselective.

[3]Since $b_C+(n_t-1)b_\Delta$ bits are required for a reporting of $(\{\hat{\Delta}_{p\to k}^i\}_{i=1}^{n_t}, \hat{C}_{p\to k})$, the total overhead in terms of bits is $\sum_{m=1}^{M}(N_{S,k}n_{\text{seg},k})(b_C+(n_t-1)b_\Delta)$.

The algorithm is summarized in Table V. Note that there may be spare feedback overhead left after the allocation of segment reporting in the proposed method. In this case, the spread overhead may be allocated to users to report some new subchannels in addition to the ones allocated in the step of allocation of subchannel reporting, or it can be left unused to save feedback resource. In this paper, since only little improvement is obtained by reporting more subchannels than those allocated in the step of allocation of subchannel reporting, the spare feedback overhead is left unused.

V. NUMERICAL RESULT

Here, the performance of the proposed methods is evaluated for an OFDMA downlink system whose system parameters are summarized in Table VI. The channel length is set to be $L_k=10\cdot T_{\text{RMS},k}/T_s=2\cdot\gamma_k\cdot N_{\text{FFT}}/N_C$ for MS k, and in all figures, SNR is defined as $\text{SNR}\doteq|g_k|^2\cdot\sigma_S^2/\sigma_N^2$.

A. Estimation of Channel and γ_k

In real systems, the channel responses $\{h_{i\to k}(l)\}_{l=0}^{L_k}$, $i=1,\ldots,n_t$, have to be estimated by MS k and used for the search of the best set of cyclic delays and subchannel sum-rate calculation. Moreover, an estimation of the frequency-selectivity rate γ_k is needed if segmentation in a subchannel is implemented. Here, the estimation of $\{h_{i\to k}(l)\}_{l=0}^{L_k}$, $i=1,\ldots,n_t$, is discussed first, followed by the estimation of γ_k by using the estimated channel responses, $\{\hat{h}_{i\to k}(l)\}_{l=0}^{L_k}$, $i=1,\ldots,n_t$.

TABLE VI
SYSTEM PARAMTERS

Parameter	values
System bandwidth	10 MHz
FFT size, N_{FFT}	1024
Number of data sub-carriers	720
Number of sub-channel, N_S	30
Number of sub-carrier per sub-channel, N_C	24
Useful OFDM symbol time, $T_{\mathrm{FFT}} = N_{\mathrm{FFT}} \cdot T_S$	91.4 μs
Guard time, $T_{\mathrm{FFT}}/8$	11.4 μs
Sub-carrier spacing, $1/T_{\mathrm{FFT}}$	10.94 kHz
Sub-channel bandwidth, $B_S = N_C \cdot 1/T_{\mathrm{FFT}}$	262.56 kHz
Number of bits for a cyclic-delay reporting, b_Δ	4
Number of bits for a sub-channel capacity reporting, b_C	8
Frequency-selectivity rate for MS k, $\gamma_k \doteq B_S/(\Delta f)_{c,k}$	$1, \cdots, 12$

To estimate the channel, we adopt the channel estimator proposed in [31] and [32] with one OFDM symbol used as the pilot symbol (all subcarriers). Here, we provide a brief summary of the method. Define

$$\mathbf{Y}_{i\to k} = [Y_{i\to k}(0) \cdots Y_{i\to k}(N_{\mathrm{FFT}}-1)]^T$$
$$\mathbf{H}_{i\to k} = [H_{i\to k}(0) \cdots H_{i\to k}(N_{\mathrm{FFT}}-1)]^T$$
$$\mathbf{h}_{i\to k} = [h_{i\to k}(0) \cdots h_{i\to k}(L_k)]^T$$
$$\mathbf{N}_{i\to k} = [N_k(0) \cdots N_k(N_{\mathrm{FFT}}-1)]^T$$

where T denotes transpose of a matrix or a vector. From (4), we have, at the pilot OFDM symbol

$$\begin{aligned}\mathbf{Y}_{i\to k} &= g_k \mathbf{H}_{i\to k} \odot \mathbf{S}_{i\to k} + \mathbf{N}_{i\to k}\\ &= g_k \mathbf{F}\begin{bmatrix}\mathbf{h}_{i\to k}\\ 0\end{bmatrix} \odot \mathbf{S}_{i\to k} + \mathbf{N}_{i\to k}\end{aligned} \quad (23)$$

where $\mathbf{S}_{i\to k} = [S_{i\to k}(0) \cdots S_{i\to k}(N_{\mathrm{FFT}}-1)]^T$ is the vector of pilot symbols, $\mathbf{F}$ is the FFT matrix with size N_{FFT}, and $\odot$ denotes the Hadamard product. Without loss of generality, we assume $\mathbf{S}_{i\to k} = [1, 1, \ldots, 1]^T$. In addition, the channel length is assumed equal to the guard interval, i.e., $L_k = N_g$ because it is not known in advance. By separating the signal subspace from the noise-only subspace, the pilot OFDM symbol can be rewritten as

$$\mathbf{Y}_{i\to k} = g_k[\mathbf{F}_h \mathbf{F}_n]\begin{bmatrix}\mathbf{h}_{i\to k}\\ 0\end{bmatrix} + \mathbf{N}_{i\to k}. \quad (24)$$

Using (24), $\hat{\mathbf{H}}_{i\to k}$ can be then estimated by [31], [32]

$$\hat{\mathbf{H}}_{i\to k} = \mathbf{F}_h \mathbf{F}_h^{\#} \mathbf{Y}_{i\to k} \quad (25)$$
$$\hat{\mathbf{h}}_{i\to k} = \mathbf{F}^{-1} \hat{\mathbf{H}}_{i\to k} \quad (26)$$

where $\mathbf{F}_h^{\#} = (\mathbf{F}_h^H \mathbf{F}_h)^{-1}\mathbf{F}_h^H$, and H denotes the Hermitian transpose of a matrix or a vector.

Using the estimates $\{\hat{h}_{i\to k}(l)\}_{l=0}^{L_k}$, $i = 1, \ldots, n_t$, the channel selectivity rate of MS k can be estimated as follows. Recall that $\gamma_k \doteq B_S/(\Delta f)_{c,k}$, where B_S is the subchannel bandwidth, $(\Delta f)_{c,\,k} \doteq 1/(5T_{\mathrm{RMS},k})$ is the channel coherent bandwidth, and $T_{\mathrm{RMS},k}$ is the RMS delay spread. B_S is a known system parameter; thus, there is no need for estimation. $(\Delta f)_{c,k}$ can be estimated by $(\hat{\Delta f})_{c,k} = 1/(5\hat{T}_{\mathrm{RMS},k})$, where $\hat{T}_{\mathrm{RMS},k}$ is an estimated RMS delay spread given by

$$\hat{T}_{\mathrm{RMS},k} = \frac{1}{n_t}\sum_{i=1}^{n_t} \hat{T}^i_{\mathrm{RMS},k} \quad (27)$$

where $\hat{T}^i_{\mathrm{RMS},k} = \sqrt{((\sum_{l=0}^{L_k}(\tau_l - \hat{\tau}_a^i)^2 |\hat{h}_{i\to k}(l)|^2)/(\sum_{l=0}^{L_k}|\hat{h}_{i\to k}(l)|^2))}$ is the estimate of the RMS delay spread for the channel from antenna i, $\hat{\tau}_a^i = ((\sum_{l=0}^{L_k}\tau_l|\hat{h}_{i\to k}(l)|^2)/(\sum_{l=0}^{L_k}|\hat{h}_{i\to k}(l)|^2))$, and $\tau_l = lT_s$. Finally, with $\hat{T}_{\mathrm{RMS},k}$, $\hat{\gamma}_k$ is calculated by $\hat{\gamma}_k = B_S \cdot (5\hat{T}_{\mathrm{RMS},k})$.

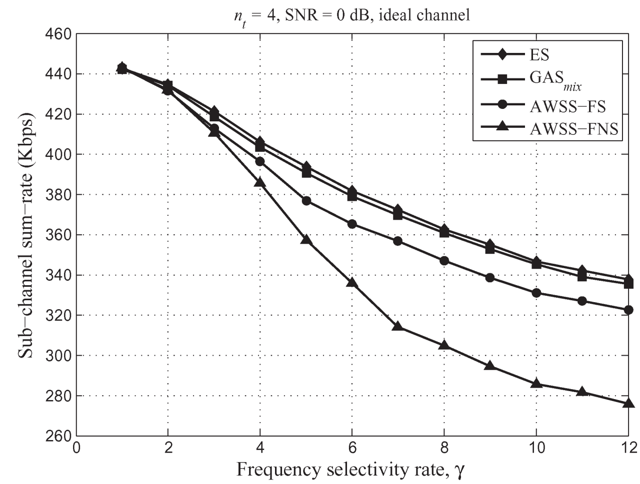

Fig. 4. Comparisons of cyclic-delay search methods under different frequency-selectivity rates.

B. Performance and Comparisons

Here, the performance of the proposed methods is presented and compared first with an ideal channel estimation, followed by the effects of nonideal channel estimation given in Fig. 11.

Fig. 4 compares the proposed cyclic-delay search methods under different frequency-selectivity rates, with the optimal ES as a benchmark. The optimized set of parameters ($K = 50, \kappa_{\mathrm{surv}} = 0.5, P_{\mathrm{mute}} = 0.1$) obtained in [18] with $N_{\mathrm{iter}} = 5$ are used here for GAS$_{\mathrm{mix}}$. The subchannel sum rate in the figure is obtained by averaging over 10^5 channel realizations. As shown, for $\gamma = 1$, all search methods have a similar performance, whereas for $\gamma > 1$, both GAS$_{\mathrm{mix}}$ and AWSS-FS outperform AWSS-FNS, with GAS$_{\mathrm{mix}}$ performing better than AWSS-FS. As one might expect, the larger the frequency-selectivity rate is, the more significant improvement is achieved with GAS$_{\mathrm{mix}}$ and AWSS-FS. In addition, the optimal ES performs only slightly better GAS$_{\mathrm{mix}}$ for $\gamma > 1$, but at the expense of huge computational complexity. In fact, in Table III, the real multiplications needed (per cyclic-delay set search) in this case are 2.85×10^6, 1.75×10^5, and 1.04×10^4 for ES, GAS$_{\mathrm{mix}}$, and AWSS-FS, respectively. For AWSS-FNS, on the other hand, only 18 real multiplications are needed, but it

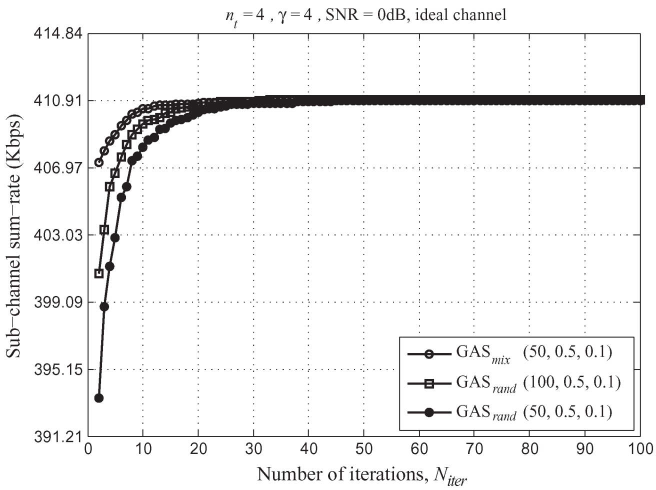

Fig. 5. Convergence behaviors of GAS_{mix} and GAS_{rand}.

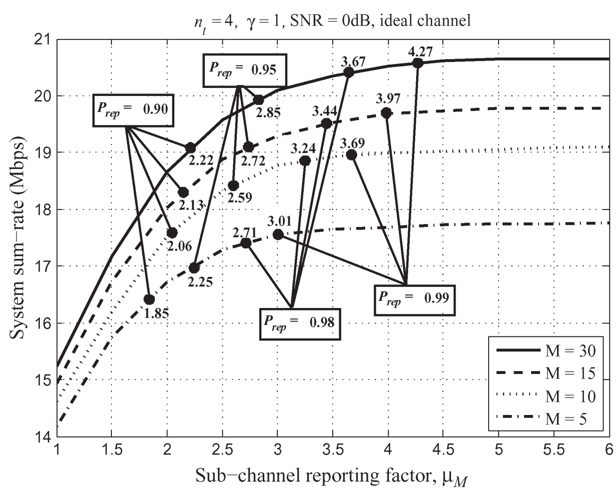

Fig. 6. Effects of μ_M on system sum rate.

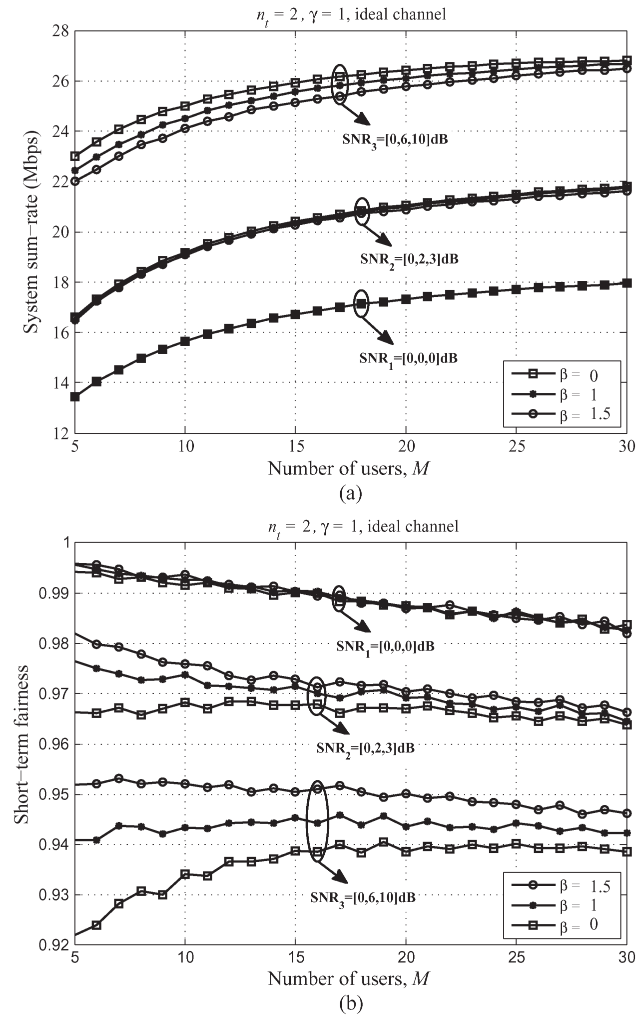

Fig. 7. Effects of β on system performance. (a) System sum rate. (b) User fairness.

suffers from significant performance degradation for a large frequency-selectivity rate, as shown in the figure.

Fig. 5 shows the advantage of the proposed GAS_{mix} over GAS_{rand} in which a pure random initial population is employed as in [18]. As is shown, GAS_{mix} converges faster than GAS_{rand} even with a smaller initial population size, which leads to less complexity.

Fig. 6 shows the effect of μ_M selection on the system sum rate with $n_t = 4$ and $\gamma = 1$, which is selected to ensure that there is no segment allocation in the CDF. In addition, since $\gamma = 1$, the optimal AWSS-FNS is employed for the cyclic-delay search. In this paper, the system sum rate is obtained with the proportional-fairness scheduler given in (1) and (2) with $W = 20$, and the scheduling is done per T_{OFDM} for simulation simplicity. Furthermore, each result is an average of 50 trials with per-trial simulation time equal to $T_{\text{sim}} = 200T_{\text{OFDM}}$. As is shown in the figure, the selection of μ_M (P_{rep}) is a tradeoff between system performance and feedback overhead, and generally, $P_{\text{rep}} \geq 0.98$ is needed to have a satisfactory performance. In the following, $P_{\text{rep}} = 0.98$ is adopted because only marginal improvement is observed with $P_{\text{rep}} > 0.98$.

Fig. 7 shows the effect of β selection on the system performance, including system sum rate and user fairness with $n_t = 2$ and $\gamma = 1$. Again, since $\gamma = 1$, the AWSS-FNS is employed, and there is no segment allocation in the proposed CDF. The concept of short-term fairness in [27]–[29] is adopted here for evaluating the user fairness because it gives a measure under a short time scale. In particular, the short-term fairness F in [27] is used as follows:

$$F = \min_{t \in \{0, \tau, 2\tau, \ldots, T_{\text{sim}}\}} F(t) \tag{28}$$

$$F(t) = \frac{\left| \sum_{j \in A} R_j(t) \right|^2}{|A| \sum_{j \in A} R_j^2(t)} \tag{29}$$

where $R_j(t)$ is the average rate received by MS j at 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, $|A| = M$, and we use $\tau = 20T_{\text{OFDM}}$. Furthermore, in all simulations, users are divided into three SNR classes with users in the same class having the same received SNR. The users are equally distributed into the three SNR classes if the user number is a multiple of three. In case that the user number is not a multiple of three, the remaining unallocated users are equally distributed to the lower SNR classes. The set of SNRs are denoted by the three-tuple $\mathbf{SNR} = [\text{SNR}_1, \text{SNR}_2, \text{SNR}_3]$ (in decibels).

Fig. 7(a) and (b) shows the system sum rate and user fairness, respectively, under different βs and three SNRs, $\mathbf{SNR}_1 = [0, 0, 0]$, $\mathbf{SNR}_2 = [0, 2, 3]$, and $\mathbf{SNR}_3 = [0, 6, 10]$. As expected, for the case of $\mathbf{SNR}_1 = [0, 0, 0]$, since all users have the same average SNR, the average rate received by each user is approximately the same; therefore, the system sum rate and user fairness are not affected by β [$\alpha_k = 1/M \ \forall k$, see (21)]. In the cases of $\mathbf{SNR}_2 = [0, 2, 3]$ and $\mathbf{SNR}_3 = [0, 6, 10]$, on the other hand, the use of different β gives a tradeoff between system sum rate and user fairness; using a large β improves the user fairness but at the expense of the system sum rate. The reason is that, with a large β, a larger portion of the feedback resource is allocated to users who have received less data rate (in a worse channel condition); therefore, the user fairness is improved, but the system sum rate is sacrificed. In the following, $\beta = 1$ is employed because it provides a good balance between system sum rate and users fairness according to our extensive simulation results, including those not shown here. Furthermore, as expected, the larger the SNR difference among users, the worse the user fairness, and the system sum rate is improved for larger M because of the more gain obtained with multiuser diversity.

The fairness index in (29) is the Jain's fairness index proposed in [30]. The index is used to measure the equality of user allocations. Assume that there are a total of n users. If all the users share the same resources, then the index goes to 1, whereas the index is $1/n$ if only one user obtains the whole resources, which is the worst case. In addition, if only k of n users receive a fair share of resources, then the fairness index is k/n. Therefore, the fairness index of 0.982 for the case of $M = 30$, $\beta = 1$, and $\mathbf{SNR}_1$ can be interpreted as, on average, $29.46 = 30 \cdot 0.982$ out of 30 users get a fair share of resources.

In Fig. 8(a) and (b), we first show the merit of using the proposed CDF for the example system of $n_t = 4$ and $\mathbf{SNR}_2 = [0, 2, 3]$, where the user frequency-selectivity rate assumes the integers of 1–8 in an equally likely way. In the figure, GAS_{mix} (AWSS-FS) + AWSS-FNS denotes that the GAS_{mix} (AWSS-FS) search is used by MS k if $n_{\text{seg},k} < \text{ceil}(\gamma_k)$, and AWSS-FNS is used if $n_{\text{seg},k} = \text{ceil}(\gamma_k)$. In addition, the even subchannel feedback (ESF) denotes the traditional method in which the feedback resource is allocated evenly to users for the subchannel reporting. As shown, CDF outperforms ESF in both system sum rate and user fairness. In particular, in the system sum rate, an improvement of 3.64% (3.68%) and 4.80% (5.07%) for $M = 20$ ($M = 30$) are provided by CDF for GAS_{mix} + AWSS-FNS and AWSS-FS + AWSS-FNS, respectively. The improvement is smaller for a small M because, in this case, there is not enough feedback overhead for segment allocation, as will be discussed in more detail in the following. In Fig. 8(a) and (b), the proposed methods are also compared with MD-ACDD in [16], and the performance bound obtained by per subcarrier reporting where the optimal cyclic delays of each subcarrier are reported, along with subcarrier sum rate, to the BS by every user. In MD-ACDD, initially, each MS finds a set of cyclic delays for each of the subchannels, aiming to maximize the sum rate of the center subcarrier, and feeds it back to the BS. Then, at the BS side, after the cyclic-delay sets are received from all MSs, a book of cyclic-delay sets (of size Z) is established by choosing the Z cyclic-delay sets that have been used most frequently among all MSs; then, the book of cyclic-delay sets is broadcast periodically to all MSs. Using this book of cyclic-delay sets, at the MS side, the MS selects the cyclic-delay set that maximizes the sum rate for each subchannel and reports its index to the BS along with the sum rate of that subchannel. Since all subchannels are reported by every MS in MD-ACDD, the total feedback overhead is given by $MN_S(\log_2 Z + b_C)$ bits.

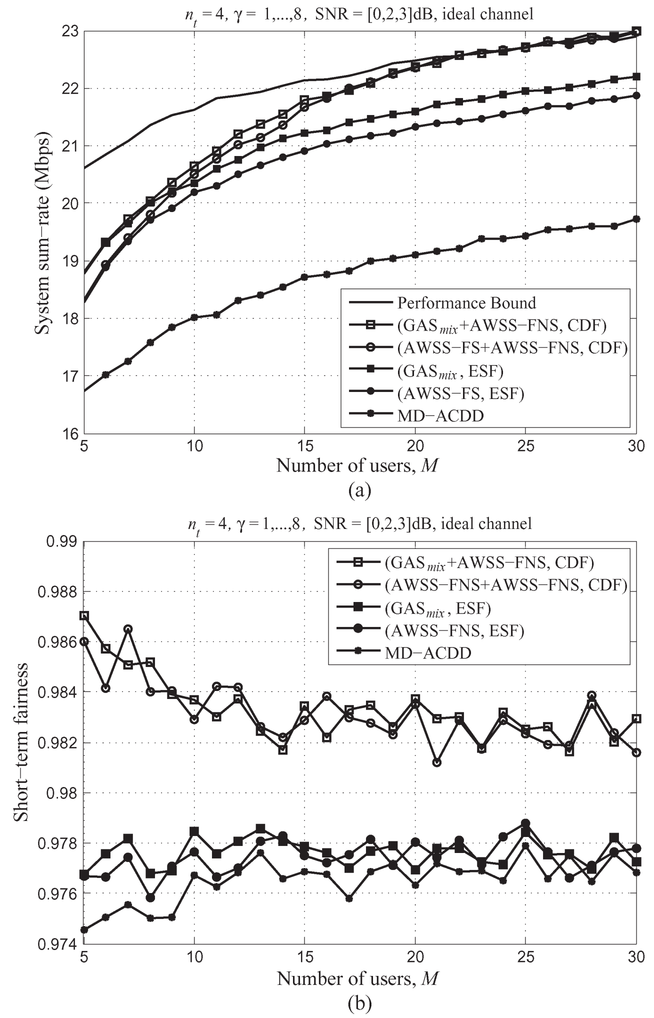

Fig. 8. System performance comparisons of different CDD-aided schedulers. (a) System sum rate. (b) User fairness.

For a fair comparison, we equalize the feedback overhead of the proposed methods and that of MD-ACDD, i.e.,

$$\sum_{k=1}^{M} N_{S,k} n_{\text{seg},k} \left((n_t - 1)b_\Delta + b_C\right) = MN_S(\log_2 Z + b_C). \tag{30}$$

Recall that, in the proposed CDF, given a total feedback overhead, subchannel allocation is done first followed by segment allocation. $Z = 16$ is adopted in the comparisons.

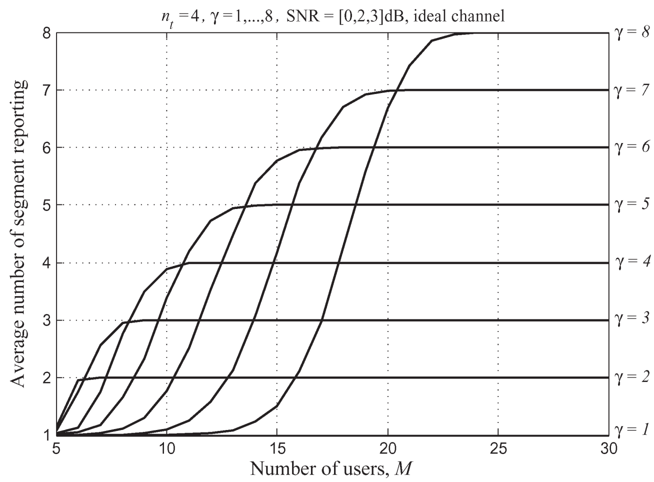

Fig. 9. Allocation of segment reporting for $(\mathrm{GAS}_{\mathrm{mix}} + \text{AWSS-FNS}, \mathrm{CDF})$ under different frequency-selectivity rates.

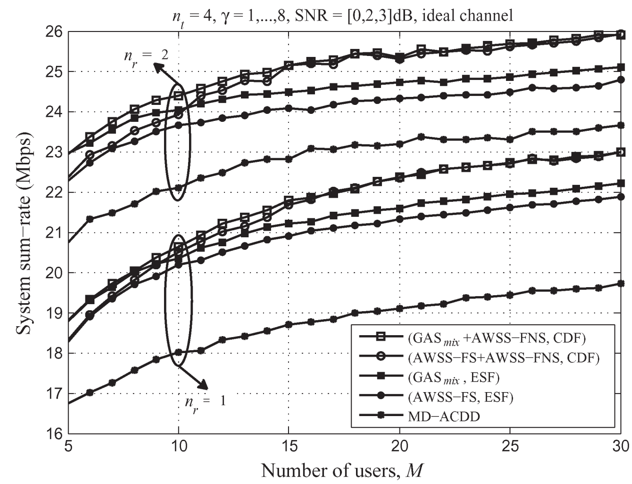

Fig. 10. System sum rates with one and two receive antennas.

As shown in Fig. 8(a) and (b), the proposed methods outperform MD-ACDD both in system sum rate and user fairness by a large margin. In particular, in the system sum rate, 17.15% (17.04%) and 16.62% (16.54%) improvement for $M = 20$ $(M = 30)$ are provided by $(\mathrm{GAS}_{\mathrm{mix}} + \text{AWSS-FNS}, \mathrm{CDF})$ and (AWSS-FS + AWSS-FNS, CDF), respectively. Using Table III, the complexity of MD-ACDD with the system parameters in Table VI is given by 1.11×10^4 for an MS in searching a subchannel with the book size of $Z = 16$, which is a slightly larger than 1.04×10^4 of AWSS-FS but has a much inferior performance. In addition, in Fig. 8(a), it is shown that there is little difference between the performance bound obtained with per subcarrier feedback and the proposed methods of $(\mathrm{GAS}_{\mathrm{mix}} + \text{AWSS-FNS}, \mathrm{CDF})$ and (AWSS-FS + AWSS-FNS, CDF) for $M > 20$, whereas the difference becomes more prominent for $M < 15$. This is due to the fact that, for a smaller M, there is not enough feedback overhead to be allocated to high frequency-selectivity users for segment reporting, as shown in Fig. 9, where for $M = 15$, only about 1.5 and 4 segment reports are allocated to users with $\gamma = 8$ and $\gamma = 7$, respectively. Ideally, $n_{\mathrm{seg},k} = \mathrm{ceil}(\gamma_k)$ should be allocated to MS k for the best performance. This same reason explains why the improvement of CDF over ESF becomes smaller for small M, as observed in Fig. 8(a).

Fig. 10 compares the system sum rates with one and two receive antennas. In the case of two antennas, the maximal-ratio combining is employed to combine the received signals. As can be expected, receive diversity improves the system sum rate for all methods. Still, the proposed methods provide a large gain over the MD-ACDD even for the two-receive-antenna case due to the newly designed cyclic-delay search methods and CDF, although the gain becomes smaller, as compared with the case of a single receive antenna. This is reasonable because the multiuser diversity gain will become smaller if there is a large order of receive diversity.

Fig. 11 shows the effect of nonperfect channel estimation on the system sum rates with the proposed methods (AWSS-FS + AWSS-FNS, CDF) and $(\mathrm{GAS}_{\mathrm{mix}} + \text{AWSS-FNS}, \mathrm{CDF})$. In our system, nonperfect channel estimation results in errors in cyclic-delay search and γ_k estimation. The performance degradation shown in Fig. 11 is the composite effect of both errors. As shown, however, only a slight degradation is observed both in system sum rate and user fairness. In particular, performance degradation rates of 0.97% and 0.90% are observed for

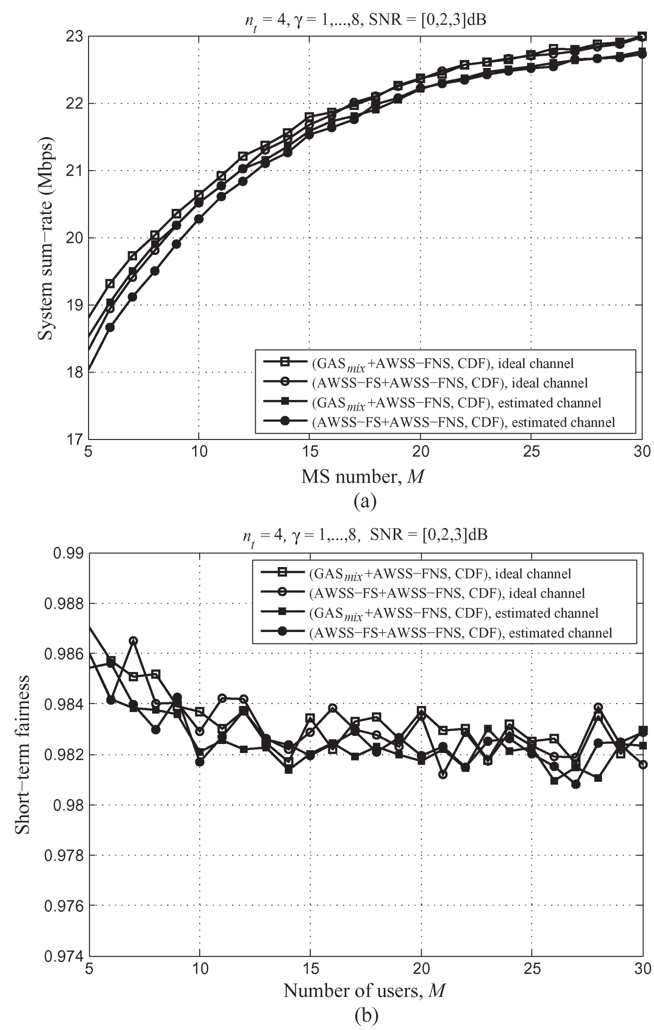

Fig. 11. Effects of nonperfect channel estimation on the proposed methods. (a) System sum rate. (b) User fairness.

TABLE VII
SELECTION OF INITIAL DETERMINISTIC CHROMOSOMES

Input: $H_{i\to k}(m),\ i{=}1,\cdots,n_t,\ m{=}(p{-}1)N_C,\cdots,pN_C{-}1$

Output: $\left\{\hat{\Delta}^{i}_{p\to k}(m)\right\}^{n_t}_{i=2},\ m{=}(p{-}1)N_C,\cdots,pN_C{-}1$

for $m{=}(p{-}1)N_C$ to $pN_C{-}1$ do

  $\hat{\Delta}^{1}_{p\to k}(m){=}0$

  for $i{=}2$ to n_t do

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

    $\hat{\Delta}^{i}_{p\to k}(m){=}Q_{\Delta}\left[\frac{N_{\mathrm{FFT}}}{2\pi m}\left[\left(\angle H_{k,i-1}(m){-}\angle H_{i\to k}(m)\right){+}2\pi n\right]\right]$

  end for

end for

(AWSS-FS + AWSS-FNS, CDF) and ($\mathrm{GAS}_{\mathrm{mix}}$ + AWSS-FNS, CDF) with $M = 30$, respectively.

VI. CONCLUSION

CDD-aided frequency-selective scheduling has been an important technique in improving the effectiveness of multiuser diversity in OFDMA downlink systems. This paper has optimized the design of the CDD-aided frequency-selective scheduling from the aspects of cyclic-delay search and scheduling-information feedback to improve system sum rate and user fairness. Three new search methods are proposed to optimize the design of cyclic delays that results in higher subchannel sum rate either in the selective or nonselective subchannel environments. A channel-dependent method is proposed to optimize the scheduling-information feedback based on the user frequency-selectivity rate and a principle of proportional fairness. The optimized CDD-aided scheduler with the proposed new methods is shown to provide significant performance improvement over the traditional MD-ACDD method.

APPENDIX
SELECTION OF DETERMINISTIC CHROMOSOMES FOR INITIAL POPULATION

As discussed in Section III, a mixture of random and deterministic chromosomes is employed to constitute the initial population. The selection of the deterministic part is summarized here. Suppose subchannel p is to be scheduled to MS k. From (5) and (6), the frequency response of the subcarriers m of subchannel p is given by $H_k(m)$ (with $\psi_i(m) = 0$), where

$$H_k(m) = \frac{1}{\sqrt{n_t}} \sum_{i=1}^{n_t} e^{-j\frac{2\pi m \Delta^{i}_{p\to k}}{N_{\mathrm{FFT}}}} H_{i\to k}(m) \qquad \text{(A.1)}$$

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

$$m =a\,(p-1)N_C, \ldots, pN_C - 1. \qquad \text{(A.2)}$$

The idea of the selection of the deterministic chromosomes is that for each subcarrier, a particular set of quantized CD-values $\{\Delta^{i}_{p\to k}(m)\}^{n_t}_{i=1}$ is selected to maximize $|H_k(m)|^2$, i.e., to maximize the subcarrier sum rate and used as one of the initial chromosomes. The optimal $\{\hat{\Delta}^{i}_{p\to k}(m)\}^{n_t}_{i=1}$ can be obtained with ES but that can be quite complex. Instead, the simple algorithm given in Table VII is proposed for the selection.

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