Imperfect Channel Estimation and Its Effect on Uplink FDMA Resource Management

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***Abstract*—In this paper, we investigate the capacity maximization problem for uplink spatial division multiple access (SDMA)/ single carrier frequency division multiple access (SC-FDMA), under imperfect channel conditions. In fact, we improve our previous work and introduce a pilot assisted estimation method along with a sub-optimal power projection method based on users' spatial correlation, which chooses the users for each resource block (RB). We assume a single-input multiple-output (SIMO) scheme with correlation at receive antenna. Numerical analysis verifies that the proposed scheme improves the SE considerably at a target defined fairness level. We also investigate the effect of variations of different system design parameters , i.e., RB size, number of receive antenna, etc, on the system spectral efficiency, when channel state information is not perfect.**

***Index Terms*—SC-FDMA, SIMO, SDMA, Multiuser Scheduling, Spatial Correlation, Resource Allocation, Uplink, Spectral Efficiency, Fairness.**

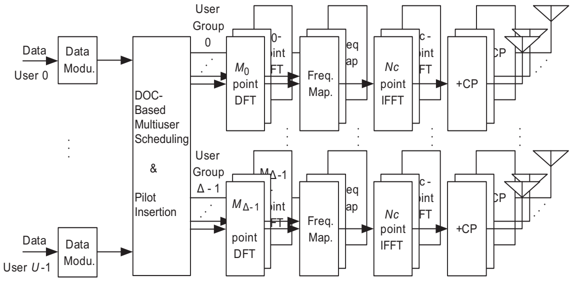
I. INTRODUCTION

Wireless communication is always in need for higher data rates. As a result, adaptive resource allocation and scheduling algorithms are proposed to improve the spectral efficiency (SE). Single-carrier frequency division multiple access (SC-FDMA) [1], [2] transmission is a novel technique used in the uplink of the 3GPP long term evolution (LTE) [3]. SC-FDMA has the advantage of reduced peak-to-average power ratio (PAPR) [4] compared to orthogonal frequency division multiple access (OFDMA), which reduces the complexity in the design of user terminal. Multiple-input multiple-output (MIMO) techniques can improve the SC-FDMA scheme significantly by allowing spatial diversity and assigning more than one user to each resource block (RB). Combining MIMO SC-FDMA with multiuser scheduling techniques can further improve the SE, especially in dense environments with larger number of users. However, the recent scheduling algorithms mainly focus on designing the algorithms and assume perfect channel state information (CSI). The works which consider at the same time, the scheduling problem and channel estimation are scarce. Channel estimation is an important issue and must be taken into consideration jointly with scheduling problem. This motivates us to think about a new method to improve the scheduling algorithms, while considering the imperfect CSI problem at the same time.

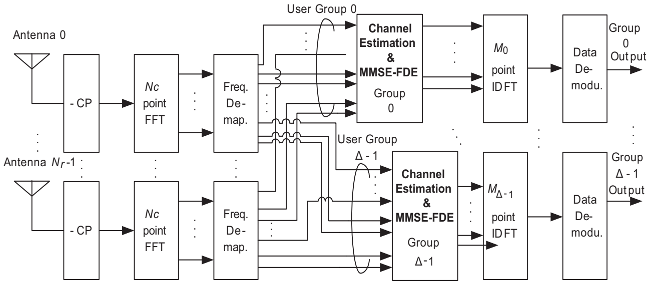
The authors in [5] consider a joint subcarrier, bit, and power allocation algorithm to minimize the total transmit power subject to bit error rate (BER) and rate constraints in downlink OFDMA. This algorithm has high computational complexity. Based on this work many other research works are proposed to reduce the complexity. In [6], authors introduced a priority based sequential scheduling criteria to achieve a better capacity compared with previous works at the cost of losing much proportional fairness among users. In [7], authors propose the use of codebook aided algorithms for joint user pairing and RA in virtual MIMO (V-MIMO) SC-FDMA. They consider two criteria for user pairing, i.e., V-MIMO channel capacity and bit error rate after equalization. This work is based on user pairing with a pairing criteria different than ours. Moreover, their RA algorithm is not adaptive with system parameters.

In [8] we proposed a multiuser scheduling and RA technique for uplink single-input multiple-output (SIMO) SC-FDMA under perfect CSI condition. In this paper, we develop our work in [8] for the case with imperfect CSI and reallistic channel estimation. We first present the signal processing at the transmitter and receiver side as well as the user's output signal-to-interference ratio (SINR) at the base station (BS). Later, we introduce our plot structure and pilot-based channel estimation procedure. Finally, we introduce our scheduling and RA algorithm, which schedules users for each RB using a low-complexity algorithm based on the concept of users' mutual degree of correlation (DOC). Our proposed algorithm determines the optimal RB size and the number of simultaneous users which should access the uplink, using a concatenated probabilistic neural network (PNN) structure. The PNN is first trained offline and then runs in online mode. Simulation results are provided to evaluate the performance of our algorithm under imperfect CSI based on different system design parameters.

The remainder of this paper is organized as follows. In Section II, SIMO SC-FDMA uplink signal transmission scheme is presented along with the SINR expression after equalization at the receiver. Section III discusses our proposed fairness-controlled multiuser scheduling and RA algorithm. Section IV discusses the simulation results and the evaluation of our algorithm. Finally, section V concludes the paper.



(a) Transmitter structure



(b) Receiver structure

Fig. 1. SIMO SC-FDMA transceiver structure.

II. MULTIUSER SC-FDMA UPLINK SIGNAL TRANSMISSION

The Multiuser SIMO SC-FDMA uplink transceiver is illustrated in Fig. 1. We use fast Fourier transform (FFT) sample-spaced discrete-time signal representation. A block transmission of M_δ symbols using N_r-antenna receive diversity reception is considered.

At the u_δth ($u_\delta = 0, \ldots, U_\delta$–1) user transmitter of δth RB, the M_δ-symbol block $\{s_{u_\delta}(n); n = 0, \ldots, M_\delta - 1\}$ is transformed by M_δ-point discrete Fourier transform (DFT) into the frequency-domain signal $\{S_{u_\delta}(k); k = 0, \ldots, M_\delta–1\}$ and then mapped over ($N_c = M_0 + M_1 + ... + M_{\Delta-1}$) subcarriers. We assume a total of ($U = U_0 + U_1 + ... + U_{\Delta-1}$) users in the system.

In this paper, we consider a localized spectrum mapping for the multiuser SIMO SC-FDMA transmitter. The frequency-domain signal after spectrum mapping is transformed back to the time-domain signal by applying N_c-point inverse FFT (IFFT). Last N_g samples of each N_c-sample block are copied as a cyclic prefix (CP) and inserted at the beginning of each block to make the received symbol block to be a circular convolution of the transmitted symbol block and the channel impulse response in order to avoid inter block interference (IBI). We assume that the CP is longer than the maximum path delay of the signal.

The CP-inserted signal block is transmitted over a frequency-selective fading channel. At the BS receiver, the received signal block at the n_rth receive antenna $\{r_{n_r}(n); n = 0, \ldots, N_c - 1\}$ after the removal of the CP is transformed by applying N_c-point FFT into the frequency-domain signal $\{R_{n_r}(k); k = 0, \ldots, N_c - 1\}$. Spectrum de-mapping is done to restore each user's spectrum. However, the MUI is present since we schedule each RB for transmission of more than one user. A simple MMSE-FDE is performed to suppress the MUI and recover the signal. Finally, a block of M_δ soft decision variables is obtained by applying M_δ-point inverse DFT (IDFT) to the frequency-domain signal.

A. Spectrum Mapping and Transmit Signal

DFT output of the u_δth user is given by

$$S_{u_\delta}(k) = \sqrt{\frac{1}{M_\delta}} \sum_{n=0}^{M_\delta - 1} s_{u_\delta}(n) \exp\left(-j2\pi k \frac{n}{M_\delta}\right). \tag{1}$$

The u_δth user's frequency-domain signal $\{S'_{u_\delta}(k);\ k = 0, \ldots, N_c - 1\}$ after spectrum mapping can be expressed as

$$S'_{u_\delta}(k) = \begin{cases} S_{u_\delta}(k - \sum_{s=0}^{\delta} M_s) & k = M_\delta, \ldots, 2M_\delta - 1 \\ 0 & otherwise \end{cases}. \tag{2}$$

An N_c-point IFFT is applied to $\{S'_u(k)\}$ to obtain the transmit time-domain signal $\{s_u(n)\}$, which is given by

$$s_{u_\delta}(n) = \sqrt{\frac{1}{N_c}} \sum_{k=0}^{N_c - 1} S'_{u_\delta}(k) \exp\left(j2\pi n \frac{k}{N_c}\right), \forall n \in \{-N_g, ..., N_c - 1\} \tag{3}$$

B. Channel Model

A frequency-selective fading is considered with the channel impulse response of u_δth user at n_rth antenna given by

$$h_{u_\delta, n_r}(\tau) = \sum_{l=0}^{L-1} h_{u_\delta, n_r} \mathbf{D}(\tau - \tau_{u_\delta, l}), \tag{4}$$

where the propagation channel is assumed to be an L-path block fading channel, each path being subjected to independent fading. h_{u_δ, n_r} and $\tau_{u_\delta, l}$ are respectively the complex-valued Rayleigh path gain and time delay of the lth path ($l = 0, \ldots, L$–1) between the u_δth user's transmitter and the n_rth ($n_r = 0, \ldots, N_r$–1) receive antenna of the BS. $\mathbf{D}(\tau)$ is the delta function. Please note that h_{u_δ, n_r} satisfies $\sum_{l=0}^{L-1} \mathbf{E}\{|h_{u_\delta, n_r}|^2\} = 1$, where $\mathbf{E} = \{.\}$ is the expectation operator.

The received signal at the n_rth antenna is given by

$$\begin{aligned} &r_{n_r}(n) = \\ &\sum_{\delta=0}^{\Delta-1} \sum_{u_\delta=0}^{U_\delta - 1} \sum_{l=0}^{L-1} \sqrt{P_{u_\delta}} h_{u_\delta, n_r} s_{u_\delta}(n - \tau_{u_\delta, l}) + n_{n_r}(n), \end{aligned} \tag{5}$$

where P_{u_δ} is the transmit power of u_δth user, $n_{n_r}(n)$ is the zero-mean complex Gaussian noise with variance $2N_0/T_s$ with N_0 being the single-sided power spectrum density of the additive white Gaussian noise (AWGN) and T_s the symbol duration.

C. Received signal and spectrum de-mapping

N_c-point FFT is applied to $\{r_{n_r}(n); n = 0, \ldots, N_c - 1\}$ to transform it into the frequency-domain signal $\{R_{n_r}(k); k = 0, \ldots, N_c - 1\}$. $R_{n_r}(n)$ is given by

$$\begin{aligned} R_{n_r}(k) &= \sqrt{\frac{1}{N_c}} \sum_{n=0}^{N_c - 1} r_{n_r}(n) \exp\left(-j2\pi k \frac{n}{N_c}\right) \\ &= \sum_{\delta=0}^{\Delta-1} \sum_{u_\delta=0}^{U_\delta - 1} \sqrt{P_{u_\delta}} H'_{u_\delta, n_r}(k) S'_{u_\delta}(k) + N_{n_r}(k), \end{aligned} \tag{6}$$

Algorithm 1 : Adaptive Scheduling and RA Algorithm.

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Input:   Target $E_b/N_0$, $U$, $\mathbf{F}$, $N_c$, $N_r$ and $\mathbf{H}' \in \mathbb{C}^{N_c \times N_r \times U}$
Output: $\Delta^*$, $M_\delta^*$, $U_\delta^*$ and Allocation Vector $\mathcal{S}_\delta$
  $\hat{U} \leftarrow \mathcal{G}(E_b/N_0, \mathbf{F}, N_r)$
  $\Delta^* \leftarrow \mathcal{F}(E_b/N_0, \hat{U}, N_r)$
  $M_\delta^* \leftarrow N_c/\Delta^*$
Initialization: $\mathcal{B} = \{0, 1, ..., \Delta^* - 1\}$; $\mathcal{U} = \{0, 1, ..., U\}$;
$U_\delta^* \leftarrow \hat{U}/\Delta^*$
while do
    $\mathcal{S}_\delta \leftarrow \emptyset, \quad \forall \delta \in \mathcal{B}$
    for $\forall \delta \in \mathcal{B}$ do
        Find $u_\delta^* = \arg\max_{j \in \mathcal{U}} \| \mathbf{H}_j^\delta \|^2$, where
        $\mathbf{H}_j^\delta \in \mathbb{C}^{(\delta M_\delta^* + 1 : (\delta+1) M_\delta^*) \times N_r \times j}$ is a subspace of $\mathbf{H}'$
        $\mathcal{S}_\delta \leftarrow \mathcal{S}_\delta \bigcup \{u_\delta^*\}$,  $\mathcal{U} \leftarrow \mathcal{U} \setminus \{u_\delta^*\}$
        while $|\mathcal{S}_\delta| < U_\delta^*$ do
            $\bar{u_\delta} = \arg\min_{j \in \mathcal{U}} \sum_{i \in \mathcal{S}_\delta} \left( \| \mathbf{H}_i^\delta (\mathbf{H}_j^\delta)^H \|^2 \,/\, \| \mathbf{H}_i^\delta \|^2 \| \mathbf{H}_j^\delta \|^2 \right)$
            $\mathcal{S}_\delta \leftarrow \mathcal{S}_\delta \bigcup \{\bar{u_\delta}\}$,  $\mathcal{U} \leftarrow \mathcal{U} \setminus \{\bar{u_\delta}\}$
        end while
    end for
    Calculate the fairness factor $\mathbf{F}^*$ and $\epsilon = |\mathbf{F}^* - \mathbf{F}|$
    if $\epsilon \leq \epsilon^*$ then
        EXIT While
    else
        Adjust $\hat{U}$ accordingly
    end if
end while
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where $H'_{u_\delta,n_r}(k)$ and $N_{n_r}(k)$ are respectively the channel gain and the noise due to the AWGN, given by

$$\begin{cases} H'_{u_\delta,n_r}(k) = \sum_{l=0}^{L-1} h_{u_\delta,n_r} \exp\left(-j2\pi k \frac{\tau_{u_\delta,l}}{N_c}\right) \\ N_{n_r}(k) = \frac{1}{N_c} \sum_{n=0}^{N_c-1} n_{n_r}(n) \exp\left(-j2\pi k \frac{n}{N_c}\right). \end{cases} \tag{7}$$

The spectrum de-mapping is applied to $\{R_{n_r}(k)\}$ to obtain the u_δth user's frequency-domain signal $\{R_{u_\delta,n_r}(k);\ k = M_\delta, \ldots, 2M_\delta - 1\}$ at δth RB, as well as the channel gain $\{H_{u,n_r}(k);\ k = M_\delta, \ldots, 2M_\delta - 1\}$ according to

$$\begin{cases} R_{u_\delta,n_r}(k) = R_{n_r}(k + \sum_{s=0}^{\delta} M_s) \\ H_{u_\delta,n_r}(k) = H'_{u,n_r}(k + \sum_{s=0}^{\delta} M_s) \end{cases}, \forall k \in \{M_\delta, \ldots, 2M_\delta - 1\}. \tag{8}$$

After FDE on each frequency to suppress the MUI and ISI, the received signal of desired user, u'_δ, in δth RB is given by

$$\begin{aligned} \hat{R}_{u'_\delta}(k) = \sum_{n_r=1}^{N_r-1} W_{u'_\delta,n_r}(k) R_{u_\delta,n_r}(k) = \sqrt{P_{u'_\delta}} \hat{H}_{u'_\delta}(k) S'_{u'_\delta}(k) \\ + \sum_{u_\delta=0, u_\delta \neq u'_\delta}^{U_\delta-1} \sqrt{P_{u_\delta}} \hat{H}_{u_\delta}(k) S'_{u_\delta}(k) + \hat{N}_{u'_\delta}(k), \end{aligned} \tag{9}$$

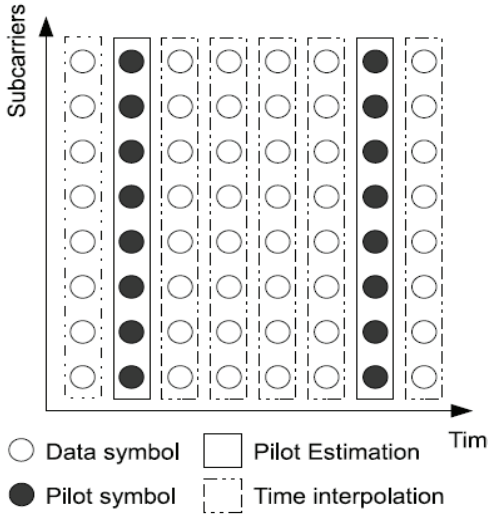

Fig. 2. Pilot structure.

where $W_{u'_\delta,n_r}(k)$ is the MMSE-FDE equalization weight for u'_δth user on frequency k and is given by

$$W_{u'_\delta,n_r}(k) = \frac{P_{u'_\delta} H^*_{u'_\delta,n_r}(k)}{\sum_{u_\delta=0}^{U_\delta-1} P_{u_\delta} \left| H_{u_\delta,n_r}(k) \right|^2 + N_0}, \tag{10}$$

and we define

$$\mathbf{W}_{u'_\delta}(k) = \left[W_{u'_\delta,1}(k), .., W_{u'_\delta,N_r}(k) \right], \tag{11}$$

as the weight vector of u'_δth user on frequency k.

$\hat{H}_{u_\delta}(k)$ and $\hat{N}_{u_\delta}(k)$ are respectively the equivalent channel gain and the noise after FDE, given by

$$\begin{cases} \hat{H}_{u_\delta}(k) = \sum_{n_r=1}^{N_r-1} W_{u'_\delta,n_r}(k) H_{u_\delta,n_r}(k) \\ \hat{N}_{u_\delta}(k) = \sum_{n_r=1}^{N_r-1} W_{u'_\delta,n_r}(k) N_{u_\delta,n_r}(k). \end{cases} \tag{12}$$

Finally, the time domain estimate is obtained by applying M_δ-point IDFT to $S_{u'_\delta}(k); k = u'_\delta, \ldots, M_\delta - 1\}$ as

$$\begin{aligned} \hat{r}_{u'_\delta}(n) &= \frac{1}{M_\delta} \sum_{k=0}^{M_\delta-1} \hat{R}_{u'_\delta}(k) \exp\left(j2\pi n \frac{k}{M_\delta} \right) \\ &= \hat{s}_{u'_\delta}(n) + I(n) + \hat{z}(n). \end{aligned} \tag{13}$$

where $\hat{s}_{u'_\delta}$ is the desired signal, $I(n)$ is the ISI+MUI term and $\hat{z}(n)$ is the noise component. After calculating the power of each component in (13) based on a Gaussian approximation, the final SINR expression is given by

$$\gamma_{u'_\delta} = \frac{\frac{P_{u'_\delta}}{M_\delta N_0} \left| \sum_{k=0}^{M_\delta-1} \hat{H}_{u'_\delta}(k) \right|^2}{\sum_{u_\delta=0}^{U_\delta-1} \frac{P_{u_\delta}}{M_\delta N_0} \sum_{k=0}^{M_\delta-1} \left| \hat{H}_{u_\delta}(k) \right|^2 - \frac{P_{u'_\delta}}{M_\delta N_0} \left| \sum_{k=0}^{M_\delta-1} \hat{H}_{u'_\delta}(k) \right|^2 + \sum_{k=0}^{M_\delta-1} \left| W_{u'_\delta,n_r} \right|^2}. \tag{14}$$

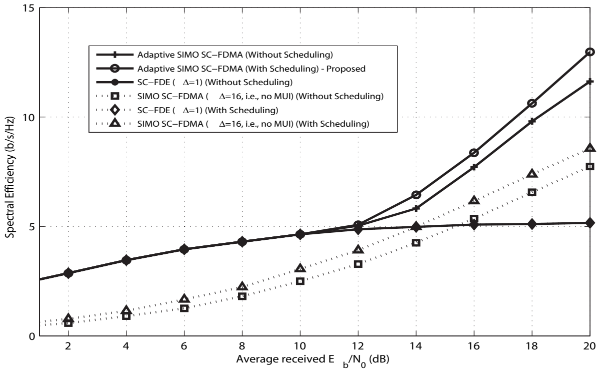

Fig. 3. Spectral efficiency *vs* average received SNR for different resource allocation scenarios, $N_r = 6$, $U = 32$, target $\mathbf{F} = 0.8$ and perfect CSI.

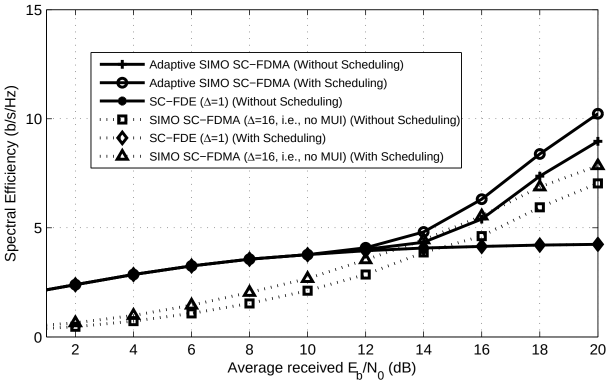

Fig. 4. Spectral efficiency *vs* average received SNR for different resource allocation scenarios, $N_r = 6$, $U = 32$, target $\mathbf{F} = 0.8$ and imperfect CSI.

D. Pilot Structure and Channel Estimation

Pilot is a kind of reference signal, which is important to the estimation of outputs. In the 3GPP LTE uplink application, there are two types of blocks in each subframe, i.e., long blocks and short blocks. The long blocks are used for control and/or data transmission, while the short blocks can be used for either control/data transmission or reference signals, which is a called, *pilot*. In this work, we assumed that the short blocks are only used for pilot transmission. A number of pilots will increase the accuracy of estimation, but it will decrease the efficiency, because there isn't any new information in the pilot symbols. Fig. 2 shows the pilot structure. We consider a least square (LS) channel estimator and assume that all the subcarriers on short blocks are occupied by pilots. For those blocks where the pilots are allocated over the whole space of subcarriers at a time, the LS channel estimation in frequency domain simplifies to divide the Fourier transformed received symbols with known transmitted pilot symbols. However, in long blocks there is no reference symbols at all, so we use an interpolation method similar to [9].

III. Adaptive Scheduling and RA Algorithm

The detailed procedure for our scheduling and RA algorithm is presented in Algorithm 1. We simplify the optimization by assuming that all RBs have the same size, i.e., $M_0 = ... = M_{\Delta-1} = N_c/\Delta$, and the number of users assigned on each RB is $U_0 = ... = U_{\Delta-1} = U/\Delta$. At first, based on the desired target fairness, the PNN algorithm gives a rough estimate of the number of simultaneous users, $\hat{U}$, which should be chosen for uplink connection. In the second step the PNN defines the optimum RB size, Δ^*, which depends on the assigned target SNR for the system, number of receive antennas and total number of users. The PNN algorithm, is trained first using a comprehensive gathered set of data in offline mode and then adaptively determines Δ^* and $\hat{U}$ in online mode. In Algorithm 1, instead of assigning users randomly to each RB, we chose users based on their DOC metric as follows; For each RB, the first user is chosen as the one with the highest channel gain, the second users is chosen among remaining users with the lowest power projection metric with the first user. The third user is chosen as the one with the lowest sum mutual power projection with previous users and so on. At the end the fairness index will be calculated based on the achieved throughput of all the users in the system. If its difference with the actual fairness index is more than an allowed threshold then, $\hat{U}$ will be adjusted accordingly till desirable outcome is reached. We define the fairness index according to $\mathbf{F} = \left(\sum_{u=0}^{U-1} C_u\right)^2 / \left(U \cdot \sum_{u=0}^{U-1} C_u^2\right)$, where C_u is each user's achieved throughput. As the fairness becomes higher, $\mathbf{F}$ approaches 1. On the other hand, as the fairness becomes lower, $\mathbf{F}$ approaches $1/U$.

IV. Computer Simulation

The simulation parameters are summarized in Table I.

Fig. 3 shows the spectral efficiency as a function of average received SNR for different scheduling and RA schemes in the presence of a fixed fairness index, $\mathbf{F} = 0.8$ and assuming perfect CSI. Our proposed adaptive scheme is compared with two extreme cases, i.e., SC-FDE ($\Delta = 1$) and pure SIMO SC-FDMA ($U = \Delta$), with and without the DOC-based scheduling technique. As we can see our proposed adaptive scheme,

TABLE I
Simulation Parameters

Transmitter	Data modulation	QPSK,
	Number of resource blocks	$\Delta = 1 \sim 8$
	FFT/IFFT size	$N_c = 256$
	Total Number of users	$U = 1 \sim 16$
	Total Transmit SNR	$E_s/N_0 = 0 \sim 20$dB
	Transmit Power Control	Slow TPC
Channel	Fading type	Frequency-selective block Rayleigh
	Power delay profile	L = 16-path uniform power delay profile
	Time delay	$\tau_{u,l} = l,\ l = 0 \sim L-1$
Receiver	Number of receive antennas	$N_r = 1 \sim 8$
	Equalization Type	MMSE-FDE
	Channel estimation	Pilot-Based LS Estimation

which jointly selects the RB size and schedules the users, has the dominant performance for SNRs over 10dB. However, it has a similar performance with SC-FDE for SNRs below 12dB. By comparing SC-FDE and SIMO SC-FDMA ($U = \Delta$), we observe that SC-FDE has a better performance only for SNRs below 14dB, and for SNRs over 14dB its performance degrades due to increased MUI. Fig. 4 shows similar plot to Fig. 3, however under imperfect CSI condition and based on our pilot-based channel estimation and interpolation scheme. We observe that our algorithm has still a good performance but with slight degradation due to channel estimation error.

V. Conclusion

We investigated the imperfect channel state information for multiuser scheduling and resource block allocation in uplink SIMO SC-FDMA system. A model for SIMO SC-FDMA system signal processing at the transmitter and receiver was first presented. Later, we derived the users's SINR, using a simple MMSE-FDE receiver. In order to design a low complexity algorithm for user scheduling, we proposed a grouping procedure based on the mutual degree of correlation between user's received channel vector. In order to estimate the uplink channel, we used a pilot structure along with an interpolation method. Simulation results show that our algorithm improves the spectral efficiency considerably, even under imperfect CSI conditions.

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