Spectrum Efficiency Analysis and Adaptive Transceiver Design for Single-Carrier Multiuser Transmission

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***Abstract*—In this paper, the spectrum efficiency of multiuser single carrier (SC) transmission is considered. In SC multiuser transmission, multiuser access can be realized by using interference suppression, e.g., SC frequency-domain adaptive antenna array (SC-FDAAA) transceiver, or by orthogonal frequency allocation among users, e.g., SC frequency-division multiple access (SC-FDMA) transceiver. To evaluate the system spectrum efficiency, the signal-to-interference-plus-noise ratio (SINR) at the output of the SC-FDAAA receiver and the SC-FDMA receiver is derived, respectively. The system spectrum efficiency is then evaluated and compared for both transceivers. It is shown that under the assumption of slow transmit power control, the system spectrum efficiency of the SC-FDMA transceiver does not change with the number of users, whereas the spectrum efficiency of the SC-FDAAA transceiver reaches its maximal value by an optimal number of users, which is determined by both the number of receive antennas and the target receive signal-to-noise ratio (SNR). With this observation, an SC-adaptive transceiver is proposed based on unorthogonal frequency allocation and frequency-domain interference suppression to improve the system spectrum efficiency, and the proposed scheme has been shown to be effective by numerical results.**

***Index Terms*—Adaptive transceiver design, frequency-domain interference suppression, single carrier (SC) transmission, spectrum efficiency, unorthogonal frequency allocation.**

I. Introduction

BROADBAND wireless communication is characterized by frequency-selective channel fading [1] when the data rate increases (e.g., 1 Gb/s). As a result, multicarrier transmission and single carrier (SC) transmission with frequency-domain equalization (FDE) [2], [3] have been considered candidates for dealing with frequency selectivity. A comparison between different frequency-domain receivers has been made in [4] to show that SC transmission yields better performance than orthogonal frequency-division multiplexing (OFDM) transmission in terms of both bit error rate (BER) and throughput. In broadband SC transmission with FDE, cyclic prefix (CP) inserted block transmission is used to make the received signal a circular convolution of the transmit signal and the channel response. When multiple antennas are available at the receiver side, QR-decomposition-based multiuser detection for SC transmission has been proposed and analyzed in [5]–[7]. QR-decomposition-based detection can employ multipath diversity [8], [9]. However, it has a drawback of high computational complexity when the length of channel response increases. Fortunately, multiuser detection can be realized by using frequency-domain interference suppression or by allocating orthogonal frequencies to different users to avoid multiuser interference (MUI). Multipath diversity can be achieved if the number of frequencies allocated to each user is more than N_C/L, where N_C is the block sequence length, and L is the channel length. In our previous study [10], SC frequency-domain adaptive antenna array (SC-FDAAA) has been proposed for a cellular system to suppress cochannel interference and MUI. It has been shown that the SC-FDAAA receiver can accommodate up to the-number-of-antennas users and that its performance is not sensitive to the angle-of-arrival spread of the received waveforms. In recent years, SC frequency-division multiple access (SC-FDMA [11], [12]), also known as discrete Fourier transform spread OFDM (DFT-S-OFDM) [13], which uses orthogonal frequency allocation to avoid MUI, has been adopted as uplink [link from the mobile station to the base station (BS)] multiuser access solution in Third-Generation Partnership Project Long-Term Evolution [14].

In this paper, we focus on the spectrum efficiency of SC transmission for a multiuser multiple-input multiple-output (MIMO) system. In the literature [15]–[19], the capacity of a point-to-point MIMO system has been well studied. However, in a multiuser MIMO system, multiple users are distributed within the cell, and usually, information exchange between users is difficult. In addition, when broadband SC transmission is considered, the transceiver structure becomes more complicated due to the introduction of frequency-domain signal processing. Therefore, the capacity and spectrum efficiency analysis for a point-to-point MIMO system cannot be applied to an SC multiuser MIMO system straightforwardly. On the other hand, many researchers have contributed their efforts to

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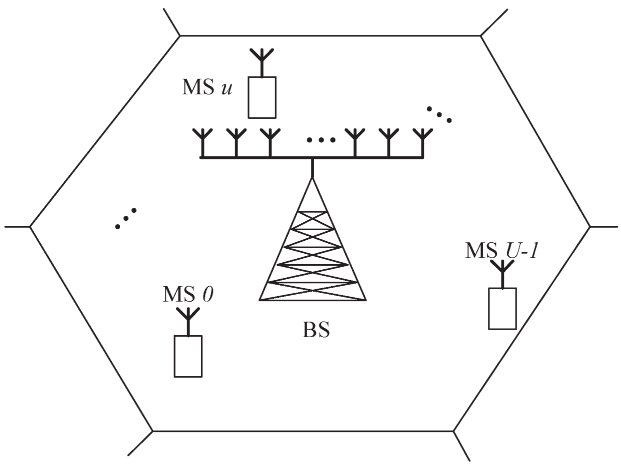

Fig. 1. SC uplink transmission in a single-cell multiuser MIMO system.

analyzing the SC transmission, e.g., FDE was applied to a direct-sequence code-division multiple access (DS-CDMA) receiver, and the BER performance of such a receiver was analyzed in [20]. However, the previous analysis on SC transmission rarely considered the receiver with multiple antennas. In this paper, we are going to analyze the spectrum efficiency of an SC multiuser MIMO system. To evaluate the system spectrum efficiency, the signal-to-interference-plus-noise ratio (SINR) at the output of the SC-FDAAA receiver and the SC-FDMA receiver is derived, respectively. The system spectrum efficiency by using the SC-FDAAA receiver and the SC-FDMA receiver is then evaluated and compared by using the SINR analytical result. Moreover, an SC-adaptive transceiver based on unorthogonal frequency allocation and frequency-domain interference suppression is proposed to improve the system spectrum efficiency.

The rest of this paper is organized as follows. A multiuser SC MIMO system model, the SC-FDAAA transceiver, and the SC-FDMA transceiver are described in Section II. The spectrum efficiency of a multiuser SC MIMO system is then analyzed, and a comparison between SC-FDAAA and SC-FDMA transceivers is carried out in Section III. With the purpose of increasing the spectrum efficiency, an SC-adaptive transceiver is proposed in Section IV. Numerical results are then given in Section V, and finally, conclusions are drawn in Section VI.

Notation: The following notations are used in this paper. Lowercase fonts denote time-domain samples; uppercase plain font and uppercase bold font, respectively, denote frequency-domain vector and matrix, unless specified otherwise; $(\cdot)^T$, $(\cdot)^*$, and $(\cdot)^H$ represent the transpose, the complex conjugate, and the complex conjugate transpose, respectively; $(\cdot)^{-1}$ represents matrix inverse; and $|\cdot|$ represents the norm of a vector.

II. Single-Carrier Multiuser Multiple-Input–Multiple-Output System

In this paper, uplink transmission in a single cell is considered. The system model is shown in Fig. 1. There are totally N_r antennas at the BS, and there are U users within the cell. Each user is equipped with a single omnidirectional antenna. A block-fading channel between each user and each antenna

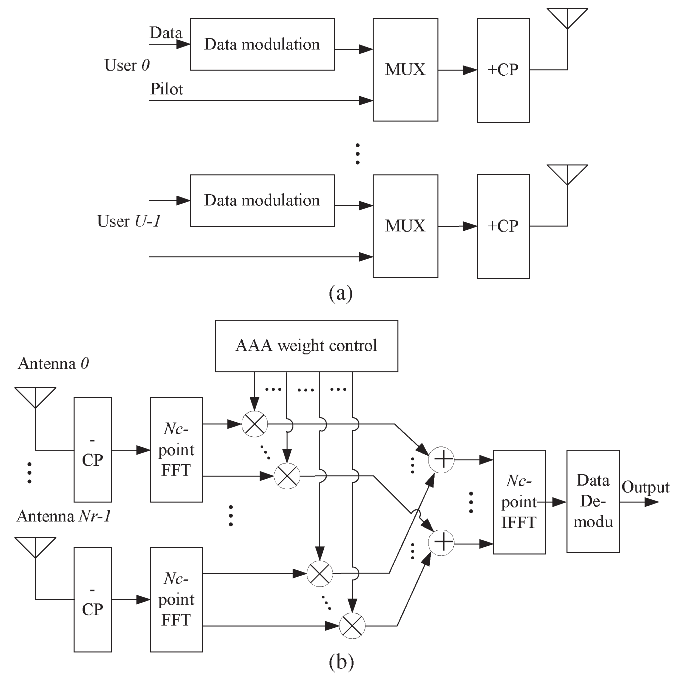

Fig. 2. Transceiver structure of SC-FDAAA. (a) Transmitter structure. (b) Receiver structure.

is assumed, i.e., the channel remains unchanged during the transmission period of a block. In this paper, symbol-spaced discrete-time representation of the signal is used. Assuming an L-path channel, the impulse response of the channel between the uth user and the mth antenna can be expressed as

$$h_{u,m}(\tau) = \sum_{l=0}^{L-1} h_{u,m,l}\delta(\tau - \tau_l) \tag{1}$$

where $h_{u,m,l}$ and τ_l are the path gain and time delay of the lth path, respectively. Path gain $h_{u,m,l}$ follows the complex Gaussian distribution and satisfies $\sum_{l=0}^{L-1} E\{|h_{u,m,l}|^2\} = 1$, where $E\{\cdot\}$ represents the expectation operation. It is assumed that the time delay τ_l is a multiple integer of the symbol duration, and $\tau_l = l$ is used. The cyclic-prefixed block signal transmission is used to make the received symbol block a circular convolution of the transmitted symbol block and the channel impulse response to avoid interblock interference. It is assumed that the CP is longer than the maximum path delay. In the following descriptions, we omit the insertion and removal of CP for simplicity.

A. Interference Suppression

One way to realize SC multiuser MIMO transmission is to use multiple antennas at the BS to suppress the MUI. Based on frequency-domain interference suppression, SC-FDAAA has been proposed in our previous study. The transceiver structure of SC-FDAAA is shown in Fig. 2. The baseband equivalent received signal block of N_C symbols at the mth antenna $\{r_m(n); n = 0 \sim N_c - 1\}$ is given by

$$r_m(n) = \sqrt{P_u d_u^{-\alpha}} \sum_{l=0}^{L-1} h_{u,m,l} s_u(n-l) + z_m(n) \tag{2}$$

where $S_u(n)$ and P_u are, respectively, the transmit signal and transmit signal power of user $(u = 0 \sim U-1)$. Symbol d_u represents the distance between the uth user and the BS, and α represents the path-loss exponent. $z_m(n)$ is the additional white Gaussian noise (AWGN). Slow transmit power control (TPC) is assumed to satisfy the same receive signal-to-noise ratio (SNR) $(E_{s,u}/N_0)_{\text{target}}$, where $E_{s,u}$ is the received symbol energy, and N_0 is the power spectrum density of noise. Therefore

$$\frac{P_u T_u d_u^{-\alpha}}{N_0} = \left(\frac{E_{s,u}}{N_0}\right)_{\text{target}} \tag{3}$$

where T_u is the symbol period. If BW_u represents the bandwidth of the uth user, then $T_u BW_u = 1$. Therefore, the transmit power of the uth user satisfies the following equation:

$$\frac{P_u}{N_0} = \left(\frac{d_u}{d}\right)^{\alpha} \cdot d^{\alpha} \cdot BW_u \cdot \left(\frac{E_{s,u}}{N_0}\right)_{\text{target}} \tag{4}$$

where d is the cell radius, and d_u/d is the normalized distance between the uth user and the BS. In this paper, path loss is assumed to be zero to simplify the analysis.

Let the transmit signal from the zeroth user be the desired signal and the transmit signals from the other users be the interfering signals. The frequency-domain representation of (2) is given by

$$\begin{aligned} R_m(k) = &\sqrt{P_0 d_0^{-\alpha}} H_{0,m}(k) S_0(k) \\ &+ \sum_{u=1}^{U-1} \sqrt{P_u d_u^{-\alpha}} H_{u,m}(k) S_u(k) + Z_m(k) \end{aligned} \tag{5}$$

where fast Fourier transform (FFT) has been used to calculate the frequency-domain components. Note that the noise component $Z_m(k)$, according to Parseval theorem [21], has the same statistical property as its counterpart in the time domain. The frequency-domain received signal vector on the kth frequency is then expressed as

$$\mathbf{R}(k) = \sqrt{P_0}\mathbf{H}_0(k) S_0(k) + \sum_{u=1}^{U-1} \sqrt{P_u}\mathbf{H}_u(k) S_u(k) + \mathbf{Z}(k) \tag{6}$$

where

$$\mathbf{H}_u(k) = \sqrt{d_u^{-\alpha}} \left[H_{u,0}(k), H_{u,1}(k), \ldots, H_{u,N_r-1}(k)\right]^T$$
$$\mathbf{Z}(k) = \left[Z_0(k)\ Z_1(k), \ldots, Z_{N_r-1}(k)\right]^T.$$

Weight control is carried out on the received signal of each antenna on each frequency to suppress the ISI and MUI, given by

$$\hat{R}_{\text{SC-FDAAA}}(k) = \mathbf{W}^T_{\text{SC-FDAAA}}(k)\mathbf{R}(k) \tag{7}$$

where $\mathbf{W}_{\text{SC-FDAAA}}(k) = [W_{\text{SC-FDAAA},0}(k), \ldots, W_{\text{SC-FDAAA},N_r-1}(k)]^T$ is the SC-FDAAA weight control vector. In the SC-FDAAA receiver [5], the minimum mean square error (MMSE) criterion is used to calculate the weight, and the weight control vector on the kth frequency is given by [22], [23]

$$\mathbf{W}_{\text{SC-FDAAA}}(k) = \mathbf{C}^{-1}_{rr}(k)\mathbf{C}_{sr}(k) \tag{8}$$

where

$$\mathbf{C}_{sr}(k) = E\left\{\sqrt{P_0} S_0(k) \mathbf{R}^*(k)\right\} \tag{9}$$

is the expectation of the cross-correlation between the received signal and the reference signal, and

$$\mathbf{C}_{rr}(k) = E\left\{\mathbf{R}(k)\mathbf{R}^H(k)\right\} \tag{10}$$

is the expectation of the self-correlation of the received signal. Substituting (6) and (8) into (7), we will have the weighted receive signal on the kth frequency, which is given by

$$\begin{aligned} \hat{R}_{\text{SC-FDAAA}}(k) = &\sqrt{P_0}\mathbf{W}^T_{\text{SC-FDAAA}}(k)\mathbf{H}_0(k) S_0(k) \\ &+ \sum_{u=1}^{U-1} \sqrt{P_u}\mathbf{W}^T_{\text{SC-FDAAA}}(k)\mathbf{H}_u(k) S_u(k) \\ &+ \mathbf{W}^T_{\text{SC-FDAAA}}(k)\mathbf{Z}(k) \end{aligned} \tag{11}$$

and the time-domain signal estimate is obtained after an N_C-point inverse FFT (IFFT), which is given as

$$\begin{aligned} &\hat{r}_{\text{SC-FDAAA}}(n) \\ &\quad = \frac{1}{N_c} \sum_{k=0}^{N_c-1} \hat{R}_{\text{SC-FDAAA}}(k) \exp\left(-j2\pi k \frac{n}{N_c}\right). \end{aligned} \tag{12}$$

B. Frequency Allocation

The other way to realize the SC MIMO multiuser transmission is by using orthogonal frequency allocation between users to avoid MUI. Here, a multiuser SC-FDMA receiver is considered as shown in Fig. 3. In SC-FDMA transmission, multiple users will access the link by occupying orthogonal frequencies. The frequencies allocated to each user can be localized or distributed, denoted by $\{\Phi_0, \Phi_1, \ldots, \Phi_{U-1}\}$. The size of $\Phi_0, \Phi_1, \ldots, \Phi_{U-1}$ is denoted by $M_0, M_1, \ldots, M_{U-1}$ and $\Phi_u = \{u_0, u_1, \ldots, u_{M_u-1}\}$, respectively. The frequency allocation should guarantee the orthogonality among users, i.e.,

$$\begin{cases} \Phi_0 \cup \Phi_1 \cdots \cup \Phi_{U-1} = \{0, 1, \ldots, N_c - 1\} \\ \Phi_m \cap \Phi_n = \varnothing (\forall m \neq n). \end{cases} \tag{13}$$

In this paper, localized equal-sized frequency allocation is assumed, i.e.,

$$\begin{cases} M_0 = M_1 = \cdots = M_{U-1} = \frac{N_c}{U} \\ \Phi_u = \left\{ \sum_{u'=0}^{u-1} M_{u'}, \sum_{u'=0}^{u-1} M_{u'} + 1, \ldots, \sum_{u'=0}^{u} M_{u'} - 1 \right\}. \end{cases} \tag{14}$$

By using SC-FDMA, the transmit signal from the uth user is given by

$$\mathbf{s}'_u = \sqrt{P'_u}\mathbf{F}^{-1}_{N_c \times N_c}\mathbf{T}_{N_c \times M_u}\mathbf{D}_{M_u \times M_u}\mathbf{s}_u \tag{15}$$

where P'_u is the transmit power of the uth user, by using slow TPC, P'_u can be calculated following (6) (note that in the SC-FDAAA scheme, all the users use the whole bandwidth, whereas in the SC-FDMA scheme, user u occupies a bandwidth that is proportional to M_u); vector $\mathbf{s}_u = [s_u(0), s_u(1), \ldots, s_u(M_u - 1)]^T$ is the sequence of transmit symbols from the uth user; $\mathbf{D}_{M_u \times M_u}$ is an $M_u \times M_u$

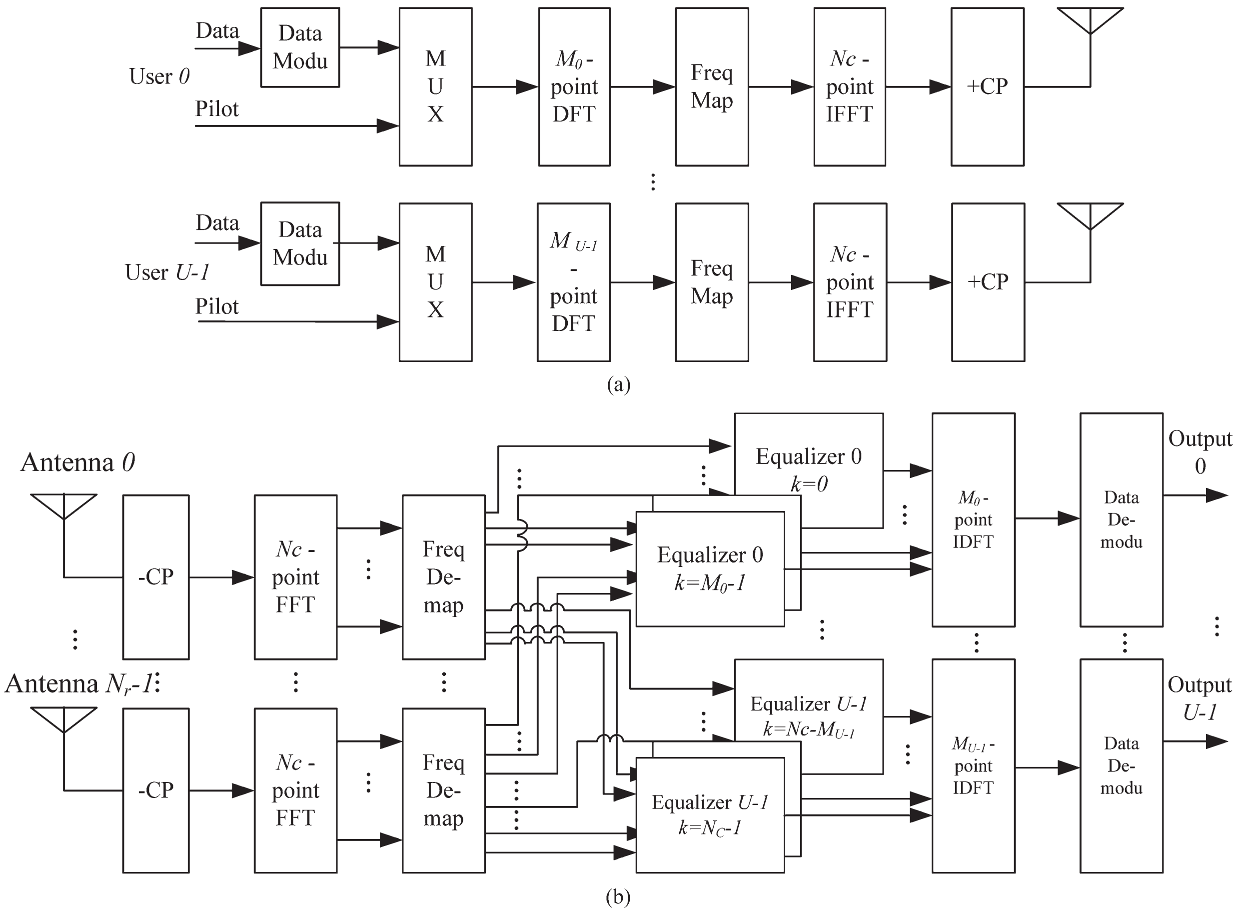

Fig. 3. Transceiver structure of SC-FDMA. (a) Transmitter structure. (b) Receiver structure.

DFT matrix $\mathbf{D}_{M_u \times M_u} = [\mathbf{d}_0^T, \mathbf{d}_1^T, \ldots, \mathbf{d}_{M_u-1}^T]$ and $\mathbf{d}_m = [1, \exp(-j2\pi(m/M_u)), \ldots, \exp(-j2\pi((M_u - 1)m/M_u))]$; $\mathbf{T}_{N_c \times M_u}$ is an $N_c \times M_u$ frequency mapping matrix; and $\mathbf{F}_{N_c \times N_c}^{-1}$ is an $N_c \times N_c$ IFFT matrix $\mathbf{F}_{N_c \times N_c}^{-1} = [\mathbf{f}_0^T, \mathbf{f}_1^T, \ldots, \mathbf{f}_{N_c-1}^T]$ and $\mathbf{f}_k = [1, \exp(j2\pi(k/N_c)), \ldots, \exp(j2\pi((N_c - 1)k/N_c))]$.

At the receiver side, N_C-point FFT and frequency demapping are performed after CP removal, and receive signals are separated and fed into the frequency-domain equalizer for each user, respectively. For the uth equalizer, the input signal on the k'th ($k' = u_0, u_1, \ldots, u_{M_u-1}$) frequency is given by

$$\mathbf{R}_u(k') = \sqrt{P_u}\mathbf{H}_u(k')S_u(k') + \mathbf{Z}_u(k') \tag{16}$$

where $\mathbf{R}_u(k') = [R_{u,0}(k'), R_{u,1}(k'), \ldots, R_{u,N_r-1}(k')]^T$ is the N_r-dimensional receive signal vector; $\mathbf{H}_u(k') = \sqrt{d_u^{-\alpha}} \times [H_{u,0}(k'), H_{u,1}(k'), \ldots, H_{u,N_r-1}(k')]^T$ is the N_r-dimensional channel response vector; and $\mathbf{Z}_u(k') = [Z_{u,0}(k'), Z_{u,1}(k'), \ldots, Z_{u,N_r-1}(k')]^T$ is the N_r-dimensional noise vector.

The equalizer can use various criteria to get the frequency-domain signal estimate. In this paper, the MMSE equalizer is assumed, and the output at the uth equalizer on the k'th frequency is given by

$$\begin{aligned}\hat{R}_{\mathrm{SC-FDMA},u}(k') &= \mathbf{W}_{\mathrm{SC-FDMA},u}^T(k')\mathbf{R}_u(k') \\ &= \sum_{m=0}^{N_r-1} W_{\mathrm{SC-FDMA},u}(k')R_{u,m}(k')\end{aligned} \tag{17}$$

where

$$W_{\mathrm{SC-FDMA},u}(k') = \frac{H_{u,m}^*(k')}{\sum_{m'=0}^{N_r-1}|H_{u,m}(k')|^2 + \left(\frac{E_{s,u}}{N_0}\right)_{\mathrm{target}}^{-1}}. \tag{18}$$

The time-domain signal estimate of the uth user is then obtained after an M_u-point IFFT, which is given as

$$\begin{aligned}&\hat{r}_{\mathrm{SC-FDMA},u}(n) \\ &\quad = \frac{1}{M_u}\sum_{k'=u_0}^{u_{M_u-1}} \hat{R}_{\mathrm{SC-FDMA}}(k') \exp\left(-j2\pi k' \frac{n}{M_u}\right).\end{aligned} \tag{19}$$

III. Spectrum Efficiency Analysis

In the AWGN channel, the system capacity can be calculated using the well-known Shannon's equation [23], i.e.,

$$c = BW \log_2(1 + \gamma) \tag{20}$$

where BW is the bandwidth, and γ is the instantaneous SNR of the signal estimate at the receiver output. A Gaussian assumption has been proven effective in [20] in approximating the statistics of interference plus noise in SC transmission. Therefore, the capacity of an SC multiuser MIMO system using the SC-FDAAA receiver and the SC-FDMA receiver can be obtained, respectively, by

$$c_{\mathrm{SC-FDAAA}} = BW \sum_{u=0}^{U-1} \log_2(1+\gamma_{\mathrm{SC-FDAAA},u}) \tag{21a}$$

$$c_{\mathrm{SC-FDMA}} = \sum_{u=0}^{U-1} BW_u \log_2(1+\gamma_{\mathrm{SC-FDMA},u}). \tag{21b}$$

The system spectrum efficiency can then be calculated as the system capacity divided by the bandwidth. In the following, the SINR of the SC-FDAAA receiver output $\gamma_{\mathrm{SC-FDAAA},u}$ and the SC-FDMA receiver output $\gamma_{\mathrm{SC-FDMA},u}$ will be analyzed, respectively.

A. Spectrum Efficiency of SC Multiuser MIMO Using SC-FDAAA Receiver

The output signal of the SC-FDAAA receiver is given in (12) and can be rewritten as

$$\hat{r}_{\mathrm{SC-FDAAA}}(n) = \hat{s}_0(n) + I(n) + \hat{z}(n) \tag{22}$$

where the desired signal component is given by

$$\hat{s}_0(n) = \sqrt{P_0} S_0(n) \sum_{k=0}^{N_c-1} \mathbf{W}^T_{\mathrm{SC-FDAAA}}(k)\mathbf{H}_0(k) \tag{23}$$

and the ISI in combination with the MUI component is given by

$$\begin{aligned} I(n) = \frac{1}{N_c} \sum_{k=0}^{N_c-1} \Bigg[& \mathbf{W}^T_{\mathrm{SC-FDAAA}}(k)\mathbf{H}_u(k) \\ & \cdot \sum_{i=0, i\neq n}^{N_c-1} \sqrt{P_0} S_0(i) \exp\left(-j2\pi k \frac{i}{N_c}\right) \\ & + \sum_{u=1}^{U-1} \sqrt{P_u} \mathbf{W}^T_{\mathrm{SC-FDAAA}}(k)\mathbf{H}_u(k) S_u(k) \\ & \times \exp\left(j2\pi k \frac{n}{N_c}\right)\Bigg] \end{aligned} \tag{24}$$

and the noise component is given by

$$\hat{z}(n) = \frac{1}{N_c} \sum_{k=0}^{N_c-1} \mathbf{W}^T_{\mathrm{SC-FDAAA}}(k)\mathbf{Z}(k) \exp\left(j2\pi k \frac{n}{N_c}\right). \tag{25}$$

We start the analysis on SINR from deriving the power of the noise component as (for detailed derivation, see Appendix A)

$$\begin{aligned} &E\left\{\hat{z}(n)\hat{z}^*(n)\right\} \\ &= \frac{N_0}{N_c} \sum_{k=0}^{N_c-1} \mathbf{W}^T_{\mathrm{SC-FDAAA}}(k) \left(\mathbf{W}^T_{\mathrm{SC-FDAAA}}(k)\right)^H. \end{aligned} \tag{26}$$

Similarly, the power of the desired signal component in (22) is obtained by

$$\begin{aligned} E\left\{\hat{s}_0(n)\hat{s}_0^*(n)\right\} = \frac{P_0}{N_c^2} & \left(\sum_{k=0}^{N_c-1} W^T_{\mathrm{SC-FDAAA}}(k)\mathbf{H}_0(k)\right) \\ & \times \left(\sum_{k=0}^{N_c-1} W^T_{\mathrm{SC-FDAAA}}(k)\mathbf{H}_0(k)\right)^H. \end{aligned} \tag{27}$$

Let $\hat{a}(n) \equiv \hat{s}_0(n) + I(n)$, power of $\hat{a}(n)$ is obtained by

$$\begin{aligned} E\left\{\hat{a}(n)\hat{a}^*(n)\right\} = \frac{P_0}{N_c} & \sum_{k=0}^{N_c-1} \mathbf{W}^T_{\mathrm{SC-FDAAA}}(k)\mathbf{H}_0(k) \\ & \times \left(\mathbf{W}^T_{\mathrm{SC-FDAAA}}(k)\mathbf{H}_0(k)\right)^H \\ & + \sum_{u=1}^{U-1} \frac{P_u}{N_c} \sum_{k=0}^{N_c-1} \mathbf{W}^T_{\mathrm{SC-FDAAA}}(k)\mathbf{H}_u(k) \\ & \times \left(\mathbf{W}^T_{\mathrm{SC-FDAAA}}(k)\mathbf{H}_u(k)\right)^H. \end{aligned} \tag{28}$$

The power of $I(n)$ can then be obtained by

$$E\left\{\hat{I}(n)\hat{I}^*(n)\right\} = E\left\{\hat{a}(n)\hat{a}^*(n)\right\} - E\left\{\hat{s}_0(n)\hat{s}_0^*(n)\right\}. \tag{29}$$

Therefore, the SINR for the desired user (user 0) at the output of the SC-FDAAA receiver can be obtained from (26), (27), and (29) as

$$\gamma_{\mathrm{SC-FDAAA}} = \frac{E\left\{\hat{s}_0(n)\hat{s}_0^*(n)\right\}}{E\left\{\hat{I}(n)\hat{I}^*(n)\right\} + E\left\{\hat{z}(n)\hat{z}^*(n)\right\}}. \tag{30}$$

The system capacity and spectrum efficiency using the SC-FDAAA transceiver can then be obtained by substituting (30) into (21a).

B. Spectrum Efficiency of SC Multiuser MIMO Using SC-FDMA Receiver

The output signal of the uth user at the SC-FDMA receiver is given in (19) and can be rewritten as

$$\begin{aligned} &\hat{r}_{\mathrm{SC-FDMA},u}(n) \\ &= \frac{1}{M_u} \sum_{k'=u_0}^{u_{M_u-1}} \Big[\sqrt{P_u}\mathbf{W}^T_{\mathrm{SC-FDMA}}(k')\mathbf{H}_u(k')S_u(k') \\ &\qquad + \mathbf{W}^T_{\mathrm{SC-FDMA}}(k')\mathbf{Z}_u(k')\Big] \\ &\quad \times \exp\left(j2\pi k' \frac{n}{M_u}\right) \\ &= \hat{s}_u(n) + \hat{I}_u(n) + \hat{z}_u(n). \end{aligned} \tag{31}$$

Since no MUI exists, the interference consists of only ISI. Similar to the previous analysis on the SC-FDAAA receiver, the power of the desired signal component, the power of the noise component, and the power of interference can be evaluated, respectively, and the SINR of the uth user's SC-FDMA output can be obtained by (32), shown at the bottom of the page. Therefore, the system capacity and spectrum efficiency using the SC-FDMA receiver can be obtained by substituting (32) into (21b).

C. Discussion

The SINR of the SC-FDAAA receiver and the SC-FDMA receiver is given in (30) and (32), respectively. Due to the frequency selectivity of the channel response, the SINR expressions are difficult to compare in their current formats. To get some insight, a special case of a single-path channel is assumed here. By using this assumption, the frequency-domain channel response will be constant for all the frequencies, and the SINR in (30) can be rewritten as (33), shown at the bottom of the page (for the detailed derivation, see Appendix B), where $H_{u,m}$ is the frequency response for the channel between the uth user and the mth antenna.

Similarly, by using the single-path assumption, the SINR in (32) can be rewritten as

$$\gamma'_{\mathrm{SC-FDMA},u} = \frac{P_u}{N_0}\left(\sum_{m=0}^{N_r-1} |H_{u,m}|^2\right). \tag{34}$$

To reveal the relationship between the SC-FDAAA receiver and the SC-FDMA receiver, we further use two extreme conditions where $N_0 \to \infty$ and $N_0 \to 0$. When condition $N_0 \to \infty$ is used, the SINR result in (33) is given by

$$\lim_{N_0\to\infty} \gamma'_{\mathrm{SC-FDAAA}} = \frac{P_0}{N_0}\left(\sum_{m=0}^{N_r-1} |H_{0,m}|^2\right). \tag{35}$$

It is noticed that the SINR limit of the SC-FDAAA receiver has the same format as that of the SC-FDMA receiver when the noise power is extremely high.

When $N_0 \to \infty$ is used, the SINR result in (33) gets its limits as

$$\lim_{N_0\to 0} \gamma'_{\mathrm{SC-FDAAA}} \approx \frac{1}{U-1}. \tag{36}$$

On the other hand, the SINR result in (34) gets its limit for $N_0 \to 0$, which is given by

$$\lim_{N_0\to 0} \gamma'_{\mathrm{SC-FDMA},u} = \infty. \tag{37}$$

It is observed that the SINR of the SC-FDMA receiver can infinitely increase when the noise power decreases; this is due to the fact that no MUI exists and that ISI also does not exist under the single-path assumption. On the other hand, when the noise power decreases, the SINR of the SC-FDAAA receiver reaches its lower bound due to the existence of MUI.

IV. Single-Carrier-Adaptive Transceiver Design

Take a system with four receive antennas ($N_r = 4$) as an example. The system spectrum efficiency given in bits per second per hertz is calculated following (21). For both the SC-FDAAA receiver and the SC-FDMA receiver, slow TPC is used, and a target total receive SNR is assumed for a fair comparison. The spectrum efficiency of the four-antenna SC multiuser MIMO system is shown in Fig. 4. In Fig. 4, the x-axis represents the number of users U, which varies from 1 to 16. It is shown that when the number of users increases, the spectrum efficiency of the system using the SC-FDMA transceiver remains unchanged. Looking at the spectrum efficiency equation, the system spectrum efficiency is the weighted sum of the

$$\gamma_{\mathrm{SC-FDMA},u} = \frac{P_u\left(\sum_{k'=u_0}^{u_{M_u-1}} \mathbf{W}^T_{\mathrm{SC-FDMA},u}(k')\mathbf{H}_u(k')\right)^2}{\left[P_u M_u \sum_{k'=u_0}^{u_{M_u-1}} \left|\mathbf{W}^T_{\mathrm{SC-FDMA},u}(k')\right|^2 |\mathbf{H}_u(k')|^2 - P_u\left(\sum_{k'=u_0}^{u_{M_u-1}} \mathbf{W}^T_{\mathrm{SC-FDMA},u}(k')\mathbf{H}_u(k')\right)^2 + N_0 M_u \sum_{k'=u_0}^{u_{M_u-1}} |\mathbf{H}_u(k')|^2\right]} \tag{32}$$

$$\gamma'_{\mathrm{SC-FDAAA}} = \frac{P_0\left(\sum_{m=0}^{N_r-1} \frac{|H_{0,m}|^2}{\sum_{u=0}^{U-1} P_u|H_{u,m}|^2+N_0}\right)^2}{\sum_{u=1}^{U-1} P_u\left(\sum_{m=0}^{N_r-1} \frac{H^*_{0,m}H_{u,m}}{\sum_{u=0}^{U-1} P_u|H_{u,m}|^2+N_0}\right)^2 + N_0\sum_{m=0}^{N_r-1} \frac{|H_{0,m}|^2}{\sum_{u=0}^{U-1} P_u|H_{u,m}|^2+N_0}} \tag{33}$$

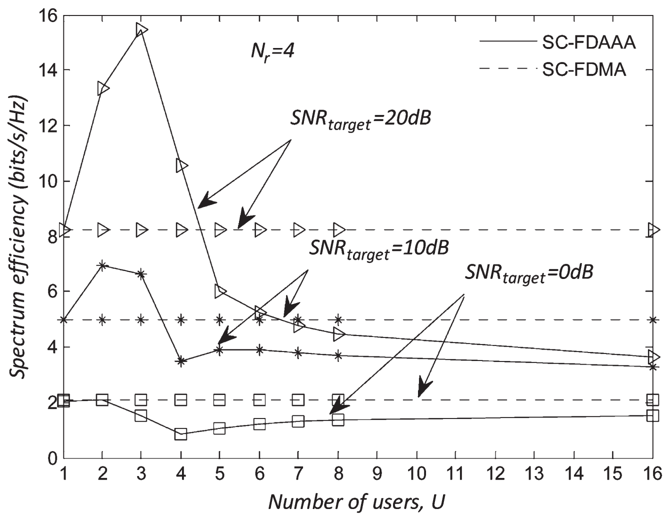

Fig. 4. Spectrum efficiency of a four-antenna multiuser SC MIMO system.

spectrum efficiency of each user. Since slow TPC is used, the spectrum efficiency for each user is almost the same to each other. Therefore, the system spectrum efficiency will not change as the number of user increases. On the other hand, the system spectrum efficiency using the SC-FDAAA transceiver experiences an increase, reaches the maximum, and then drops down when the number of users increases. According to (21), the system spectrum efficiency is the sum of the spectrum efficiency of all the users. Under the constraint of a target total receive SNR, the target receive SNR of each user decreases as the number of users increases. Meanwhile, as the number of users increases, the MUI for each user increases as well. Therefore, the system spectrum efficiency becomes a tradeoff between the increased number of users and the decreased spectrum efficiency of each user. The number of users that maximizes the system spectrum efficiency is determined by both the number of receive antennas and the target total receive SNR.

Based on the given observation, an SC-adaptive transceiver based on unorthogonal frequency allocation and frequency-domain interference suppression is proposed in this paper to improve the system spectrum efficiency, as shown in Fig. 5. In the proposed scheme, multiple users will be grouped, and frequency allocation is carried out between user groups. At the receiver side, user groups will be separated by frequency mapping, and frequency-domain interference suppression will be used for the users within the same group to suppress the MUI. The frequency allocation schemes of the SC-FDAAA transceiver, the SC-FDMA transceiver, and the proposed SC-adaptive transceiver are shown in Fig. 6 to reveal their differences. It is obvious that in the SC-FDAAA transceiver, each user takes the whole bandwidth; in the SC-FDMA transceiver, each user takes the frequencies that are orthogonal to the other users; and in the proposed SC-adaptive transceiver, users within the same group share the same frequencies, whereas the frequencies allocated to each group are orthogonal to the other groups. It should be noticed that the aforementioned SC transceivers have all kept the advantage of SC transmission. That is, they have a much lower peak-to-average-power ratio than multicarrier-modulation-based transmission.

In Fig. 5, each DFT and IDFT block in the adaptive transceiver is programmable so that they can deal with data sequences with variable lengths. In this paper, a simple user grouping and frequency allocation is used. That is, users will be grouped without considering their instantaneous channel status. In addition, localized frequency allocation is used, and the frequencies will be equally allocated to each user group. Joint user grouping and frequency allocation, with the objective of further improving the spectrum efficiency, will be proposed in our future work. The proposed transceiver will adaptively choose the user group size according to a predecision based on the calculation of spectrum efficiency, which is given by

$$\Delta_{\mathrm{opt}} = \underset{\Delta=1,2,\ldots,U}{\arg\max} \left\{ \max \left\{ \sum_{u=0}^{U/\Delta-1} \log_2(1+\gamma_{\mathrm{SC-FDAAA},u}) \right.\right. \left.\left. \frac{\Delta}{U} \sum_{u=0}^{U/\Delta-1} \log_2(1+\gamma_{\mathrm{SC-FDMA},u}) \right\} \right\}. \quad (38)$$

By using the proposed SC-adaptive transceiver, the achievable spectrum efficiency is given by

$$\bar{c}_{\mathrm{SC-adpt}} = \frac{1}{BW} \sum_{p=0}^{\Delta_{\mathrm{opt}}-1} BW_p \sum_{u=U/\Delta_{\mathrm{opt}}\cdot p}^{U/\Delta_{\mathrm{opt}}\cdot(p+1)-1} \log_2\left(1+\gamma''_{\mathrm{SC-FDAAA},u}\right) \quad (39)$$

where BW_p is the bandwidth allocated to the pth user group, and symbol $\gamma''_{\mathrm{SC-FDAAA},u}$ is the SINR of the output of the SC-adaptive transceiver and can be obtained following the previous SINR analysis for the SC-FDAAA receiver.

V. Numerical Results

Here, the analysis on the SC-FDAAA receiver and the SC-FDMA receiver for SC multiuser transmission will be testified first. The average BER performance obtained by theoretical analysis will be compared with the numerical results generated by Monte Carlo simulations. The parameters used to generate the average BER results are shown in Table I. The analysis on the SC-FDAAA receiver is testified first. By using the derived instantaneous SINR and the assumption that the interference-plus-noise component follows the Gaussian distribution, the instantaneous BER is calculated by $p_{b,\mathrm{QPSK}} = Q(\sqrt{\gamma_{\mathrm{SC-FDAAA}}})$, where $Q(\cdot)$ is the Q-function, and $\gamma_{\mathrm{SC-FDAAA}}$ is the instantaneous SINR obtained by (30). The average BER performance of an SC-FDAAA receiver can be obtained by an average over the distribution of $\{\mathbf{H}_0, \ldots, \mathbf{H}_{U-1}\}$. A four-antenna receiver is used, and slow TPC is assumed so that each user has the same average receive SNR. When the number of users vary from one (single-user case) to four (the maximal number of users that can be accommodated by a four-antenna SC-FDAAA receiver), the simulation results and theoretical results for average BER performance of user 0 are marked by "simu" and "theo," respectively, as shown in Fig. 7. A good match between the

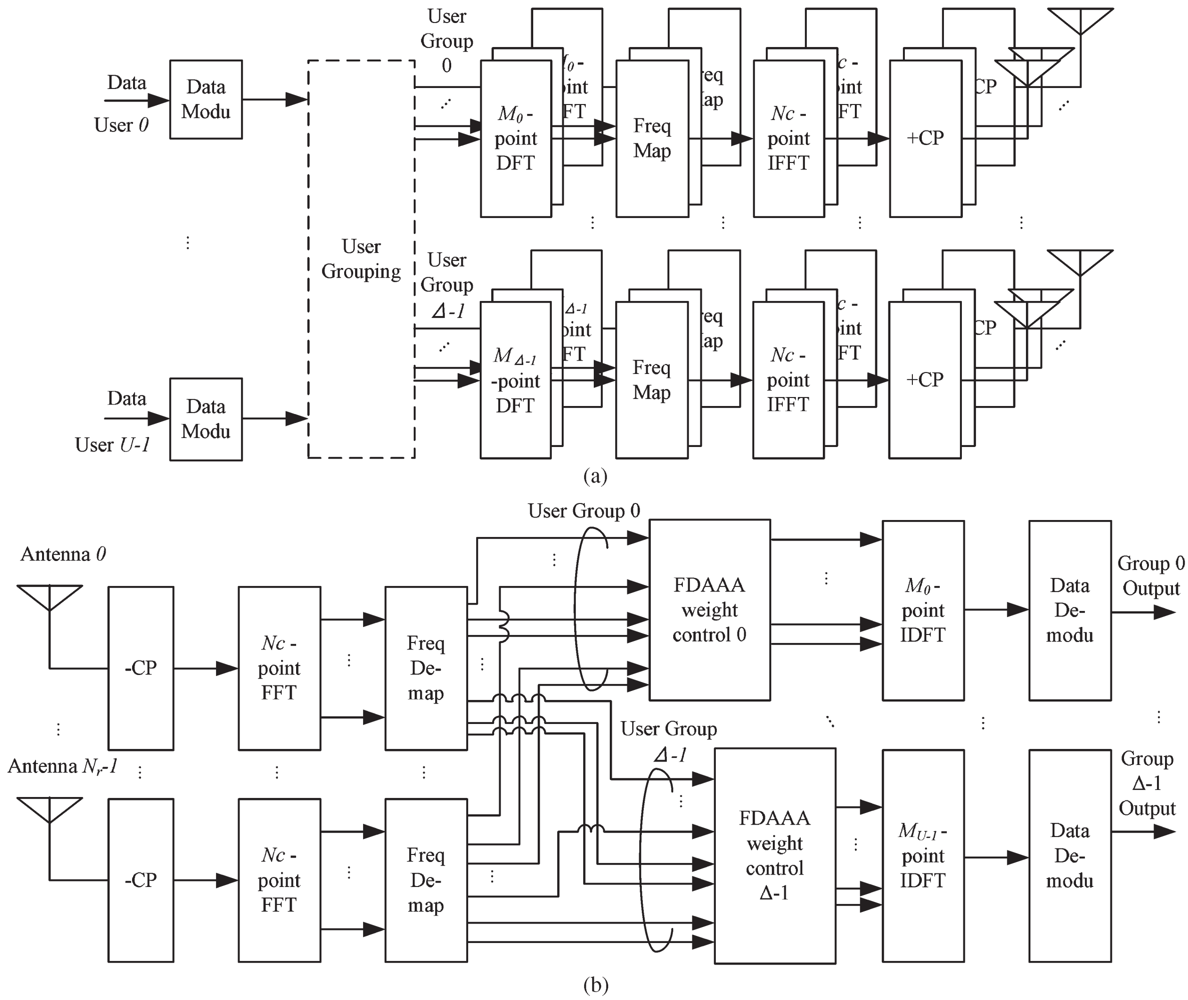

Fig. 5. SC-adaptive transceiver for multiuser MIMO system. (a) Transmitter structure. (b) Receiver structure.

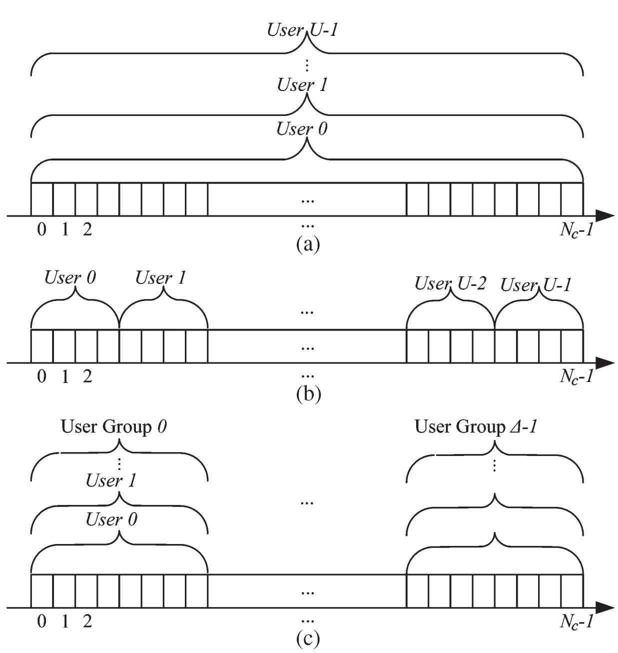

Fig. 6. Frequency allocation schemes of (a) SC-FDAAA, (b) SC-FDMA, and (c) SC-adaptive transceivers.

TABLE I
PARAMETERS FOR AVERAGE BER PERFORMANCE

Number of antennas		4
Modulation		QPSK
Transmit power control (TPC)		Slow
Target receive SNR	SC-FDAAA	-10~10dB
	SC-FDMA	-20~20dB
Number of users	SC-FDAAA	1~4
	SC-FDMA	3
Channel	Number of paths L	16
	Power delay profile	Uniform
	Estimation	Ideal
FFT points	SC-FDAAA	$N_c = 256$
	SC-FDMA	$M_0 = 128, M_1 = 64, M_2 = 64$

simulation results and the theoretical results is observed. The result verifies our proposed analysis and shows the effectiveness of the Gaussian assumption as well. It is noticed that the average BER performance experiences a significant degradation when the number of users increases. For an SC-FDAAA receiver, there exists a tradeoff between the diversity gain and the capability of interference suppression [9]. The degree of freedom

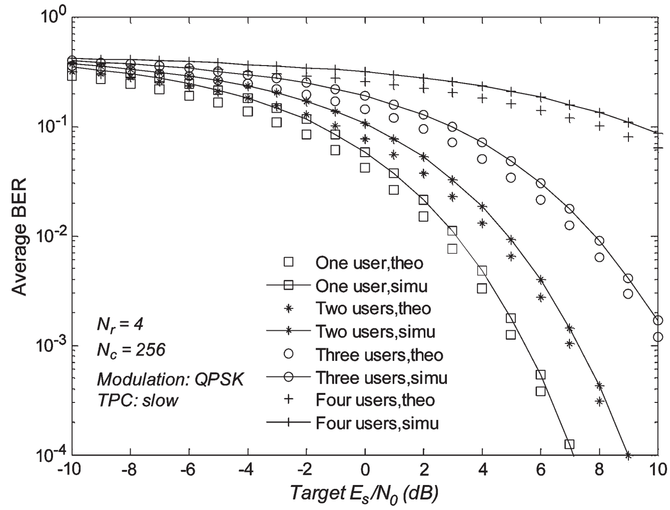

Fig. 7. Average BER performance of user 0; four-antenna SC-FDAAA receiver.

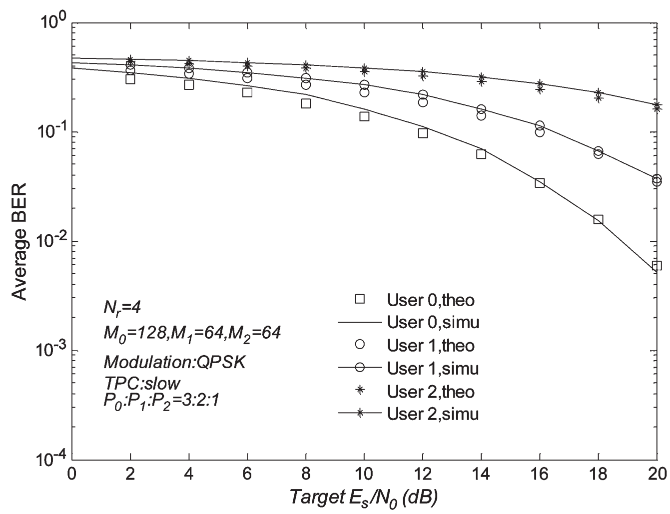

Fig. 8. Average BER performance for user 0, user 1, and user 2; SC-FDMA receiver.

TABLE II
PARAMETERS FOR SPECTRUM EFFICIENCY PERFORMANCE

Number of antennas N_r		4, 8
Modulation		QPSK
Transmit power control		Slow TPC
Target receive SNR E_s/N_0		0dB~20dB
Number of users		1~16
User distribution		Random
Channel	Number of paths L	16
	Power delay profile	Uniform
	Estimation	Ideal
FFT/IFFT points	SC-FDAAA	$N_c = 256$
	SC-FDMA	N_c/U
	SC-adaptive	Variable

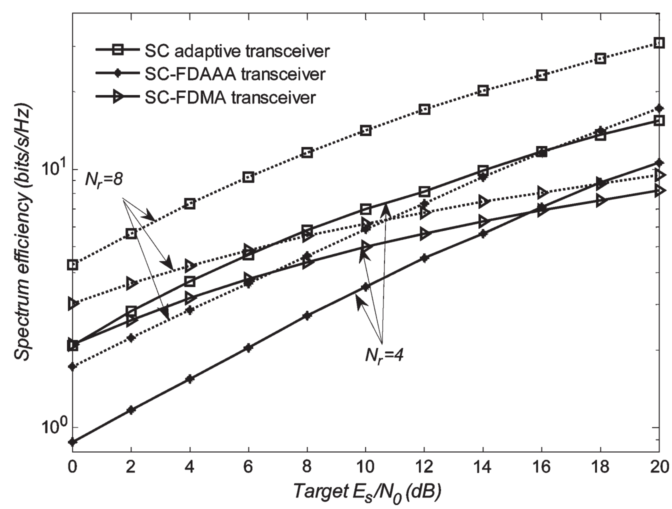

Fig. 9. Spectrum efficiency, SC multiuser MIMO with $N_r = 4$ and $N_r = 8$.

is determined by the number of receive antennas. Therefore, when the number of users increases, more degrees of freedom are used for interference suppression. For instance, for a four-antenna receiver, the diversity order reduces to one when the number of users increases to four.

The analysis for the SC-FDMA receiver is testified in the following. Here, three users are sharing the bandwidth, and it is assumed that $M_0 = 128$, $M_1 = 64$, $M_2 = 64$ and $\Phi_0 = \{0, \ldots, 127\}$, $\Phi_1 = \{128, \ldots, 191\}$, and $\Phi_2 = \{192, \ldots, 255\}$. The power allocation among users is set as $P_0 : P_1 : P_2 = 3 : 2 : 1$. The purpose of such frequency and power allocation is to yield different combinations of frequency and power among users so that the proposed analysis can be testified. The result is shown in Fig. 8. It can be observed that the simulation results match the theoretical results well, and therefore, the effectiveness of the proposed analysis has been verified.

The spectrum efficiency of the SC multiuser MIMO system is studied in the following. The parameters used to generate the spectrum efficiency are listed in Table II. The spectrum efficiency of four-antenna receiver and eight-antenna receiver SC multiuser MIMO systems is shown in Fig. 9, where the user group size used by the SC-adaptive transceiver is determined by (38) in a brute-force way, and the corresponding system spectrum efficiency is calculated following (39). The results for the other situations are not plotted to make the figure clean and easier to read.

It is shown that in the low-SNR region, the SC-FDMA transceiver can obtain better spectrum efficiency than the SC-FDAAA transceiver while the situation becomes reverse in the high-SNR region. In the low-SNR region, the MUI component in the SC-FDAAA receiver output is significant and degrades the spectrum efficiency performance. While in the high-SNR region, MUI becomes less significant, and the SC-FDAAA transceiver can benefit from the fact that each user takes the whole bandwidth. On the other hand, all the users share the bandwidth in the SC-FDMA transceiver. It is also shown that the SC-adaptive transceiver can achieve a considerable spectrum efficiency increase when comparing with both the SC-FDAAA receiver and the SC-FDMA transceiver. The spectrum efficiency increase given in percentage for the four-antenna and eight-antenna SC multiuser MIMO systems is summarized in Tables III and IV, respectively. A more significant spectrum efficiency increase by the SC-adaptive transceiver over the SC-FDAAA transceiver and the SC-FDMA receiver has been

TABLE III
SPECTRUM EFFICIENCY INCREASE (%) BY USING SC-ADAPTIVE TRANSCEIVER. $N_r = 4$

Target E_s/N_0 (dB)	0	2	4	6	8	10	12	14	16	18	20
Increase over SC-FDAAA (%)	137	140	139	129	114	99	81	75	63	53	46
Increase over SC-FDMA (%)	-	7	17	25	33	40	46	57	69	78	87

TABLE IV
SPECTRUM EFFICIENCY INCREASE (%) BY USING SC-ADAPTIVE TRANSCEIVER. $N_r = 8$

Target E_s/N_0 (dB)	0	2	4	6	8	10	12	14	16	18	20
Increase over SC-FDAAA (%)	148	152	159	159	149	140	130	115	100	90	79
Increase over SC-FDMA (%)	41	55	73	91	109	129	150	168	184	205	224

observed when $N_r = 8$. It is expected that as the number of antennas increases, the increase in spectrum efficiency achieved by the SC-adaptive transceiver will become more significant due to the fact that the brute-force search in (38) has an increased variety to maximize the spectrum efficiency.

It should be noted that in this study, no user scheduling is assumed, and a target total receive SNR is used for slow TPC. If a total transmit power constraint is used and multiuser scheduling is considered as well, the problem will become more complicated, and different conclusions might be drawn. User scheduling using total transmit power constraint remains an interesting topic for our future study.

VI. CONCLUSION

In this paper, an SC multiuser MIMO system has been considered, and the spectrum efficiency has been analyzed. The SINR of a frequency-domain-interference-suppression-based SC-FDAAA transceiver and an orthogonal-frequency-allocation-based SC-FDMA transceiver has been derived, and the system spectrum efficiency has then been evaluated and compared based on the Gaussian approximation of interference plus noise. It is shown that under the assumption of slow TPC, the spectrum efficiency of the system using the SC-FDMA transceiver remains almost unchanged when the number of users varies. On the other hand, the spectrum efficiency of the system using the SC-FDAAA transceiver achieves the maximal value by an optimal number of users, which is determined by both the number of receive antennas and the target receive SNR. Moreover, an SC-adaptive transceiver has been proposed to improve the spectrum efficiency based on unorthogonal frequency allocation and frequency-domain interference suppression. It has been shown by numerical results that the proposed scheme can effectively improve the system spectrum efficiency and that such improvement becomes more significant when the number of antennas increases. It should be noticed that the TPC scheme can greatly affect the performance of the SC-adaptive transceiver. The spectrum efficiency can be further improved by employing multiuser diversity if proper TPC and frequency allocation is used. The transmit power optimization problem remains as our further work. In addition, carrier offset will also affect the performance, and carrier offset compensation for the SC-adaptive transceiver also remains as our future work. Furthermore, nonlinear FDE [25] can improve the performance of SC transmission and should be considered in our future work as well.

APPENDIX A

The power of the noise component in (26) can be calculated by

$$\begin{aligned} &E\left\{\hat{z}(n)\hat{z}^*(n)\right\} \\ &= \frac{1}{N_c^2}\sum_{k=0}^{N_c-1}\sum_{k'=0}^{N_c-1}\Bigg(\mathbf{W}_{\mathrm{SC-FDAAA}}^T(k)E\left\{\mathbf{Z}(k)\mathbf{Z}^H(k')\right\} \\ &\qquad \times \mathbf{W}_{\mathrm{SC-FDAAA}}^H(k')\cdot\exp\left(j2\pi k\frac{n}{N_c}\right) \\ &\qquad \times \exp\left(-j2\pi k'\frac{n}{N_c}\right)\Bigg). \end{aligned} \tag{A1}$$

Since $\mathbf{Z}(k) = [Z_0(k) \quad Z_1(k) \quad \cdots \quad Z_{N_r-1}(k)]^T = \sum_{n=0}^{N_C-1}[z_0(k) \quad z_1(k) \quad \cdots \quad z_{N_r-1}(k)]\exp(-j2\pi k(n/N_c))$, we have

$$E\left\{\mathbf{Z}(k)\mathbf{Z}^H(k')\right\} = N_c N_0 \mathbf{I}_{N_r}\delta\left(k-k'\right). \tag{A2}$$

Therefore, $E\{\hat{z}(n)\hat{z}^*(n)\}$ is obtained by

$$\begin{aligned} &E\left\{\hat{z}(n)\hat{z}^*(n)\right\} \\ &= \frac{N_0}{N_c}\sum_{k=0}^{N_c-1}\mathbf{W}_{\mathrm{SC-FDAAA}}^T(k)\left(\mathbf{W}_{\mathrm{SC-FDAAA}}^T(k)\right)^H. \end{aligned} \tag{A3}$$

APPENDIX B

Under the assumption of a single-path channel, the frequency-domain channel response becomes constant for different frequencies. As a result, the inverse matrix calculation of $\mathbf{C}_{rr}^{-1}$ in (8) is given by (B1), shown on the top of the next page, where

$$E\left\{|R_m(k)|^2\right\} = \sum_{u=0}^{U-1}P_u E\left\{|H_{u,m}|^2\right\} + N_0. \tag{B2}$$

The cross-correlation calculation in (8) is given by

$$\mathbf{C}_{sr}(k) = P_0 E\left\{\left[H_{0,0}^*,\ H_{0,1}^*,\ \ldots,\ H_{0,N_r-1}^*\right]^T\right\}. \tag{B3}$$

$$\mathbf{C}_{rr}^{-1}(k) = \begin{bmatrix} \left(E\left\{|R_0(k)|^2\right\}\right)^{-1} & 0 & \cdots & 0 \\ 0 & \left(E\left\{|R_1(k)|^2\right\}\right)^{-1} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \left(E\left\{|R_{N_r-1}(k)|^2\right\}\right)^{-1} \end{bmatrix} \tag{B1}$$

$$\gamma'_{\mathrm{SC-FDAAA}} = \frac{P_0\left|\mathbf{W}_{\mathrm{SC-FDAAA}}^T\mathbf{H}_0\right|^2}{\sum_{u=0}^{U-1} P_u\left|\mathbf{W}_{\mathrm{SC-FDAAA}}^T\mathbf{H}_u\right|^2 - P_0\left|\mathbf{W}_{\mathrm{SC-FDAAA}}^T\mathbf{H}_0\right|^2 + N_0\left|\mathbf{W}_{\mathrm{SC-FDAAA}}^T\right|^2} \tag{B5}$$

The SC-FDAAA weight is then obtained by submitting (B2) and (B3) into (8), which is given by

$$\mathbf{W}'_{\mathrm{SC-FDAAA}}(k) = \left[\frac{P_0 E\left\{H_{0,0}^*\right\}}{\sum_{u=0}^{U-1} P_0 E\left\{|H_{u,0}|^2\right\} + N_0}, \ldots \right. \\ \left. \frac{P_0 E\left\{H_{0,N_r-1}^*\right\}}{\sum_{u=0}^{U-1} P_u E\left\{|H_{u,N_r-1}|^2\right\} + N_0}\right]^T. \tag{B4}$$

The SINR of the SC-FDAAA receiver is then obtained by submitting (B4) into (30), given by (B5), shown on the top of the page. Equation (33) is then obtained by submitting (B4) into (B5).

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