# Adaptive Transceiver Design for Single Carrier Transmission

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***Abstract*-In single-carrier (SC) transmission with multiple receive-antennas, multi-user access can be realized by using interference suppression. In our previous study, SC frequency -domain adaptive antenna array (SC-FDAAA) transceiver was proposed to realize frequency domain interference suppression and it was proved that SC-FDAAA transceiver can accommodate up to the number-of-receive-antennas users. However, when the number of users is larger than the number of receiver antennas, the performance of SC-FDAAA receiver will be significantly degraded. In order to accommodate a larger number of users than the number of receive antennas, an SC-adaptive transceiver is proposed in this study based on non-orthogonal frequency allocation and frequency-domain interference suppression. The effectiveness of the proposed transceiver is shown by simulation results.**

***Index terms*- Frequency allocation; Interference cancellation; Multi-user transmission; Single carrier; Spectrum efficiency**

## I. Introduction

When the data rate increases (e.g., 1Giga bits per second), wireless channel will exhibit strong frequency-selectivity due to the presence of many paths having different time delays and therefore, strong inter-symbol interference (ISI) is produced [1]. As a result, frequency-domain equalization (FDE) is necessary in the SC transmission [2].

In the broadband SC transmission with FDE, data symbol sequence is divided into blocks and the cyclic prefix (CP) is inserted into the beginning of each data block. In SC transmission with FDE, when multiple antennas are available at the receiver side, multi-user transmission can be realized by using frequency-domain interference suppression or by allocating orthogonal frequencies to different users to avoid multi-user interference (MUI).

SC frequency-domain adaptive antenna array (SC-FDAAA) was proposed for cellular system in our previous study [3] to suppress co-channel interference (CCI) as well as MUI. It has been shown that SC-FDAAA transceiver can accommodate up to the number-of-antennas users and its performance is not sensitive to the angle of arrival (AOA) spread of the received waveforms. However, when the number of users is larger than the number of receive antennas, the previously proposed SC-FDAAA transceiver will suffer a significant performance degradation due to the residual interference.

In this study, an SC adaptive transceiver is proposed to accommodate a larger number of users than the number of receive antennas based on non-orthogonal frequency allocation and frequency domain interference suppression.

The rest of the paper is organized as follows. Multi-user SC uplink transmission is modeled and SC-FDAAA transceiver is introduced in Section II, the SC adaptive transceiver is proposed in Section III; Simulation results will then be given in Section IV and finally conclusions will be drawn in Section V.

## II. Multi-user Single-Carrier Uplink Transmission Model

SC uplink transmission in a single-cell is considered. The system model is shown in Fig. 1.

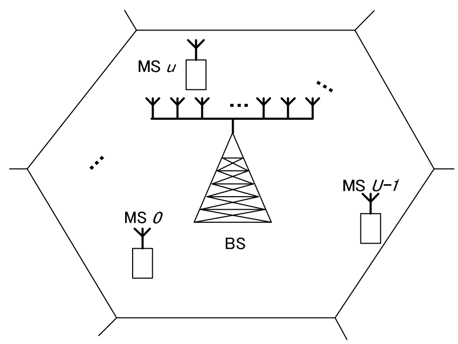



Fig. 1 Multi-user SC uplink transmission in a single-cell.

There are totally $N_r$ antennas at the BS and $U$ users within the cell and each user is equipped with one Omni antenna. A block fading channel between each pair of user and antenna is assumed, i.e., the channel remains unchanged during the transmission period of a block. In this paper, the symbol-spaced discrete time representation of the signal is used. Assuming an $L-$path channel, the impulse response of the channel between the $u^{th}$ user and the $m^{th}$ 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 $\tau_l$ are the path gain and time delay of the $l^{th}$ path, respectively. $h_{u,m,l}$ follows the complex Gaussian distribution and satisfies $\sum_{l=0}^{L-1}E\left\{\left|h_{u,m,l}\right|^2\right\}=1$, where $E\{\cdot\}$ represents the expectation operation. It is assumed that the time delay is an integer-multiple of the symbol duration and $\tau_l=l$. The cyclic-prefixed block signal transmission is used to make the received symbol block to be a circular convolution of the transmitted symbol block and the channel impulse response so as to avoid inter block interference (IBI). It is also assumed that the CP is longer than the maximum path delay of the channel. In the following, the insertion and removal of CP is omitted for simplicity.

SC-FDAAA has been proposed in our previous study. The baseband equivalent received signal block $\{r_m(n); n = 0 \sim N_c - 1\}$ of $N_c$ symbols at the $m^{th}$ antenna is given by

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

where $s_u(n)$ and $P_u$ are respectively the transmit signal and transmit signal power of user $u$ $(u = 0 \sim U-1)$. $d_u$ represents the distance between the $u^{th}$ user and the BS and $\alpha$ represents the path loss exponent. $z_m(n)$ is the AWGN noise. Slow transmit power control (TPC) is assumed in order to guarantee the average target receive signal to noise ratio ($SNR_{u,\text{target}}$) where $SNR_{u,\text{target}} = E_{u,\text{target}} / (BW_u \cdot N_0)$; $E_{u,\text{target}}$ is the target received signal energy, $BW_u$ is the bandwidth of the $u^{th}$ user and $N_0$ is power spectrum density of noise. Therefore

$$P_u \delta_u^{-\alpha} / N_0 = SNR_{u,target}, \qquad (3)$$

The transmit power of the $u^{th}$ user satisfies the following equation

$$P_u = (d_u/d)^{\alpha} \cdot d^{\alpha} \cdot SNR_{u,target} \cdot N_0, \qquad (4)$$

where $d$ is the cell radius and $d_u/d$ is the normalized distance between the $u^{th}$ user and the BS. In this study, no shadowing loss is assumed to simplify the analysis.

Let the transmit signal from the $0^{th}$ 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

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

where fast Fourier transform (FFT) has been used to calculate the frequency-domain components. Note that the noise component $Z_m(k)$, according to the Parseval's theorem [3], has the same statistical property as its counterpart in time domain. The frequency-domain received signal vector on the $k^{th}$ frequency is then expressed as

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

where $\mathbf{H}_u(k) = \sqrt{d_u^{-\alpha}} \left[ H_{u,0}(k),\ H_{u,1}(k),\ \cdots,\ H_{u,N_r-1}(k) \right]^T$ and $\mathbf{Z}(k) = \left[ Z_0(k)\ \ Z_1(k)\ \ \cdots\ \ Z_{N_r-1}(k) \right]^T$ with the superscript $^T$ representing transpose operation.

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

$$\hat{R}_{SC-FDAAA}(k) = \mathbf{W}_{SC-FDAAA}^T(k) \mathbf{R}(k), \qquad (7)$$

where $\mathbf{W}_{SC-FDAAA}(k) = \left[ W_{SC-FDAAA,0}(k), \cdots, W_{SC-FDAAA,N_r-1}(k) \right]^T$ is the SC-FDAAA weight control vector. In SC-FDAAA receiver [2], minimum mean square error (MMSE) criterion is used to calculate the weight and the weight control vector on the $k^{th}$ frequency is given by [4][5]

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

where

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

and

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

Superscript $^*$ represents the complex conjugate operation and superscript $^H$ represents the transpose conjugate operation. Substitute Eq. (6) and Eq. (8) into Eq. (7) and we will have the weighted receive signal on the $k^{th}$ frequency, given by

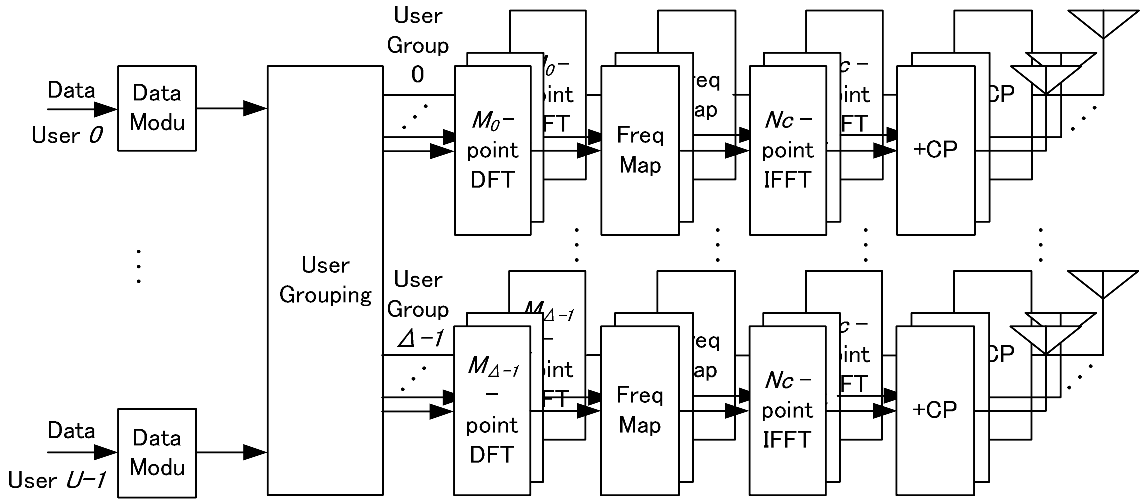
$$\begin{aligned} \hat{R}_{SC-FDAAA}(k) &= \sqrt{P_0} \mathbf{W}_{SC-FDAAA}^T(k) \mathbf{H}_0(k) S_0(k) \\ &+ \sum_{u=1}^{U-1} \sqrt{P_u} \mathbf{W}_{SC-FDAAA}^T(k) \mathbf{H}_u(k) S_u(k) + \mathbf{W}_{SC-FDAAA}^T(k) \mathbf{Z}(k) \end{aligned}, \qquad (11)$$

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

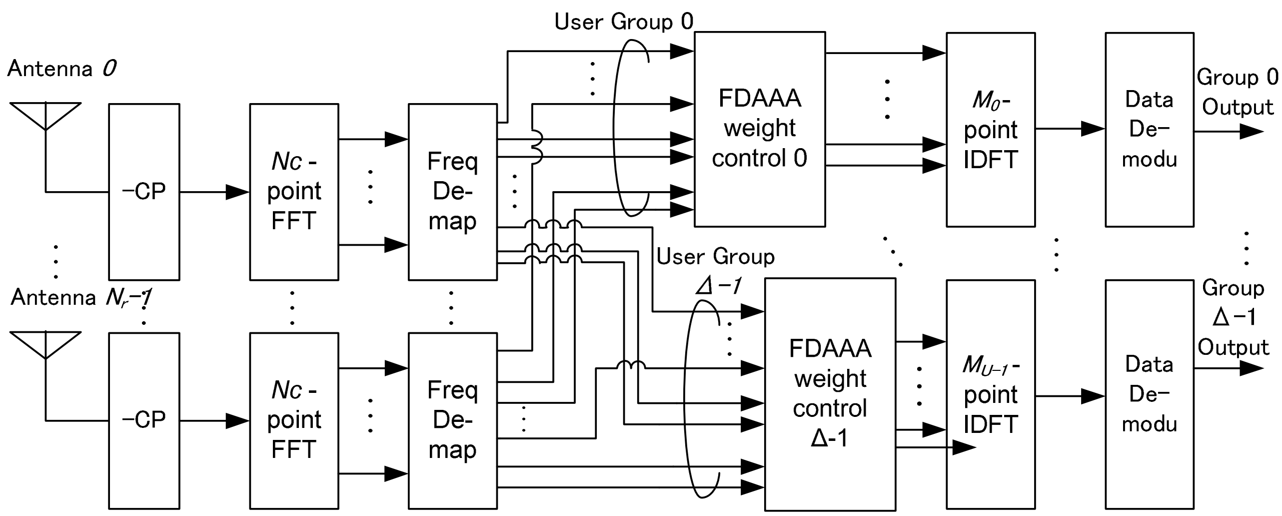
$$\begin{aligned} &\hat{r}_{SC-FDAAA}(n) \\ &= \frac{1}{N_c} \sum_{k=0}^{N_c-1} \hat{R}_{SC-FDAAA}(k) \exp\left( -j2\pi k \frac{n}{N_c} \right) \end{aligned}. \qquad (12)$$

## III. Single-carrier Adaptive Receiver

In order to accommodate a larger number of users than the number of receive antennas, an SC adaptive transceiver based on non-orthogonal frequency allocation and frequency-domain interference suppression is proposed in this study, as shown in Fig. 2. In the proposed scheme, multiple users will be grouped, and frequency allocation is carried out between user groups. In Fig. 2, each DFT and IDFT block is programmable so that they can deal with the data sequences of variable lengths. The transceiver will adaptively choose the user group size according to a pre-decision based on the calculation of spectrum efficiency. Two examples, the spectrum efficiencies as a function of user group size for a four-receive-antennas system and an eight-receive-antenna system are shown in Fig. 3 and Fig. 4, respectively.




(a) Transmitter structure




(b) Receiver structure

Fig. 2 SC adaptive transceiver for multi-user uplink transmission.

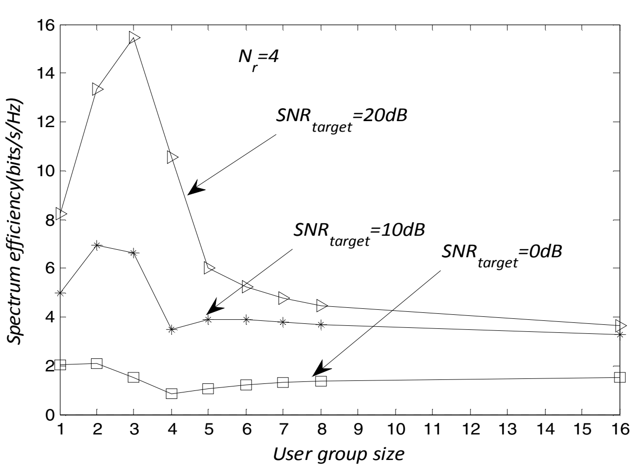



Fig. 3 Spectrum efficiency as a function of user group size, $N_r = 4$.

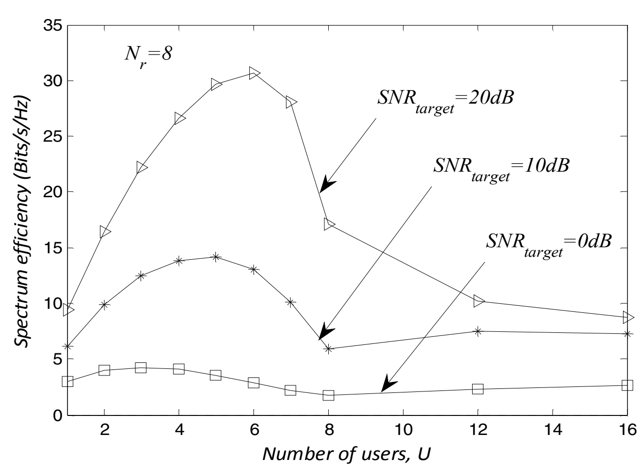



Fig. 4 Spectrum efficiency as a function of user group size, $N_r = 8$.

At the receiver side, different user groups will be separated by frequency mapping and frequency-domain interference suppression will be used to the users belonging to the same group to suppress the MUI. The difference of frequency allocation between SC-FDAAA transceiver and SC-adaptive transceiver is shown in Fig. 5.

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

$$\bar{C}_{SC-adapt} = \frac{1}{BW}\sum_{p=0}^{\Delta-1} BW_p \sum_{u=p_0}^{p_{U/\Delta-1}} \log_2\left(1+\Gamma_{SC-FDAAA,u}\right), \qquad (13)$$

where $BW$ is the total bandwidth, $\Delta$ is the number of user groups; $BW_p$ is the sub-bandwidth allocated to the $p^{th}$ user group; $\Gamma_{SC-FDAAA,u}$ is the signal to interference plus noise ratio (SINR) of the output time domain signal estimate for the $u^{th}$ user. The derivation of $\Gamma_{SC-FDAAA,u}$ itself is complex and the details are given separately in another paper.

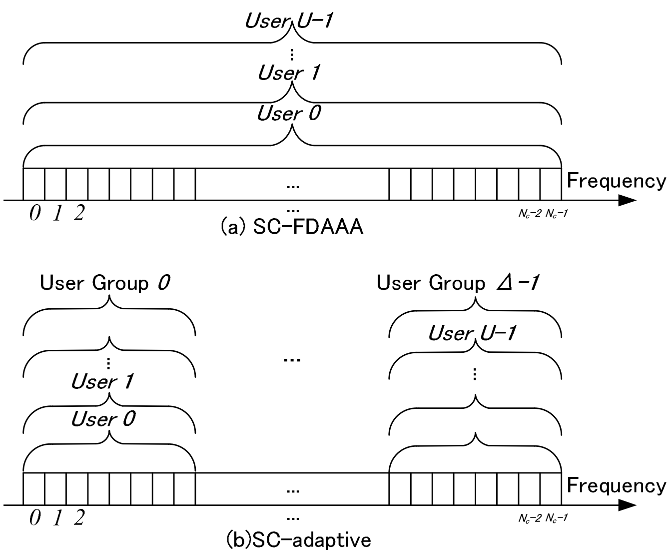



Fig. 5 Frequency allocation schemes of SC-FDAAA and SC-adaptive transceivers.

## IV. Numerical Results

In this section, spectrum efficiency given by bits/s/Hz of the multi-user SC uplink transmission using the proposed SC adaptive transceiver will be testified by simulation results generated by Monte Carlo calculations. The parameters used for numerical calculations are listed in Tab. I

TABLE I PARAMETERS

| | | |
|---|---|---|
| Number of antennas $N_r$ | | 4, 8 |
| Transmit power control | | Slow TPC |
| Target $E_s/N_0$ | | 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-adaptive | Variable |

The spectrum efficiency of a four-antenna multi-user SC uplink transmission is shown in Fig. 6. In this figure, the spectrum efficiency obtained by the SC adaptive receiver is calculated following Eq. (13); the spectrum efficiency obtained by the SC-FDAAA receiver is calculated for $U=4$ and is plotted for comparison. It is shown that the proposed SC-adaptive transceiver can achieve a considerable spectrum efficiency increase when comparing with SC-FDAAA receiver. The capacity increase given in percentage for the four-antenna multi-user SC uplink transmission is summarized in Tab. II.

The spectrum efficiency of an eight-antenna receiver multi-user SC uplink transmission is shown in Fig. 7. Similar to the four-antenna system, the spectrum efficiency obtained by the proposed SC-adaptive receiver is calculated following Eq. (13). The spectrum efficiency obtained by the SC-FDAAA transceiver is calculated for $U=8$ . The spectrum efficiency increase in percentage achieved by using SC-adaptive transceiver when $N_r = 8$ is summarized in Tab. III. From the result, a more significant spectrum efficiency increase by SC-adaptive transceiver over SC FDAAA transceiver has been observed.

TABLE II SPECTRUM EFFICIENCY INCREASE (%) BY USING SC ADAPTIVE TRANSCEIVER, $N_r = 4$

| Target $E_b/N_0$ (dB) | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Spectrum efficiency increase % over SC-FDAAA | 137 | 140 | 139 | 129 | 114 | 99 | 81 | 75 | 63 | 53 | 46 |

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

| Target $E_b/N_0$ (dB) | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Spectrum efficiency increase % over SC-FDAAA | 148 | 152 | 159 | 159 | 149 | 140 | 130 | 115 | 100 | 90 | 79 |

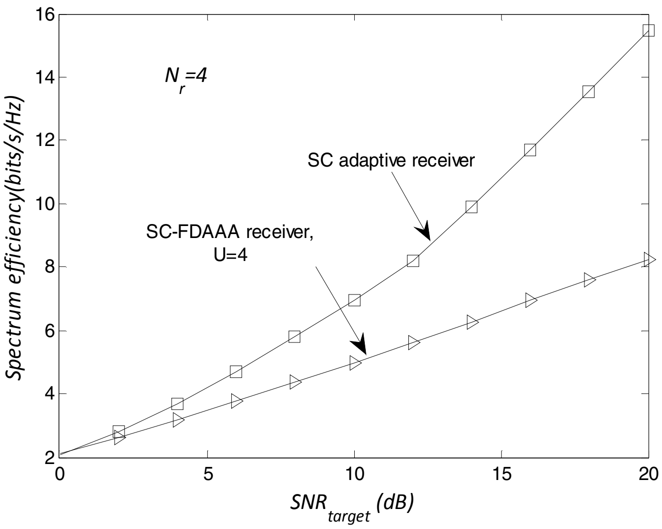



Fig. 6 Spectrum efficiency of multi-user SC uplink transmission with $N_r = 4$.

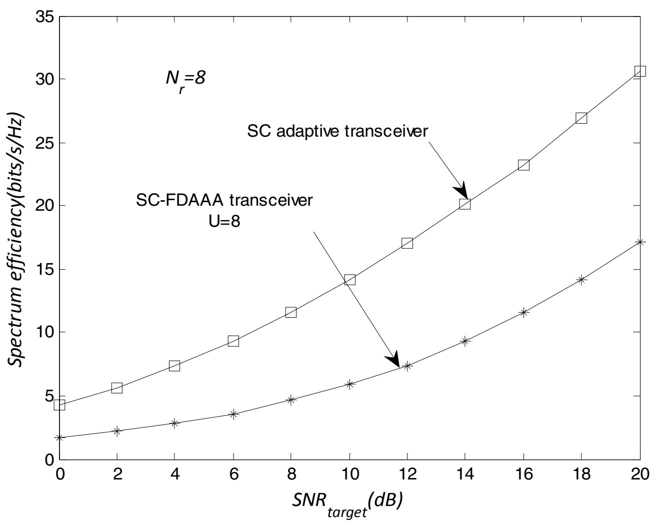



Fig. 7 Spectrum efficiency of multi-user SC uplink transmission with $N_r = 8$.

It should be noted that in this study, no multi-user scheduling is assumed and slow TPC is used for a target total receive-SNR. If a total transmit-power constraint is used and multi-user scheduling is considered as well, the problem will become more complicate and conclusions will be different. The multi-user scheduling scheme using total transmit-power constraint for multi-user SC uplink transmission remains as an interesting topic for the future study.

## V. Conclusions

In this study, multi-user SC uplink transmission was considered. In order to accommodate a larger number of users than the number of antennas, an SC-adaptive transceiver has been proposed to maximize the spectrum efficiency based on non-orthogonal frequency allocation and frequency-domain interference suppression. The effectiveness of the proposed transceiver has been verified by the simulation results.

## Acknowledgement

This work was supported in part by KDDI Research Grant Program (J110000208).

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