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MULTI-USER INTERFERENCE CANCELLATION SCHEME(S) FOR MULIPLE CARRIER FREQUENCY OFFSET COMPENSATION IN UPLINK OFDMA

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ABSTRACT

We consider the uplink of an Orthogonal Frequency Division Multiple Access (OFDMA)-based system, where each Mobile Station (MS) experiences a different Carrier Frequency Offset (CFO). Uncorrected CFOs destroy the orthogonality among subcarriers, which could cause severe Inter-Carrier Interference (ICI) and degrade the system performance considerably. In this paper, we propose a novel Multi-User Interference (MUI) cancellation scheme for uplink OFDMA, which utilizes multiple Orthogonal Frequency Division Multiplexing (OFDM)-demodulators architechture to correct and then compensate the negative effects of multiple CFOs at the receiver's side. Numerical evaluation has shown a considerable performance gain compared to the conventional receiver.

I. INTRODUCTION

Based on OFDM, OFDMA has emerged as one of the prime multiple access schemes for broadband wireless networks, e.g. Universal Mobile Telecommunications System (UMTS), the European standard for the 3G cellular mobile communications, and IEEE 802.16, the broadband wireless access standard for Wide Area Network (WAN) [10]. In OFDMA, available subcarriers are grouped into subchannels, which are assigned to different users operating simultaneously. Preserving orthogonality among these subchannels is essential, as it prevents the ICI, which consequently eliminates MUI [3].

While the orthogonality among subchannels can be maintained relatively easily in the downlink, preserving orthogonality in the uplink is much more demanding. In the uplink, the received signal is the sum of multiple signals coming from different users, each of which experiences a different CFO due mainly to oscillator instability and/or Doppler shift [9]. These relative CFOs among users destroy the orthogonality among subchannels, thus can degrade the system performance severely. Conventional CFO correction methods used in the downlink are designed for single-user system, and therefore are unable to correct multiple CFOs in the uplink. Several researching efforts have been carried out to solve the relative CFO problems of OFDMA in the OFDMA uplink scenario. [11, 9] suggests that the Base Station (BS) performs only frequency and timing estimation, whereas adjustment of the synchronization parameters is made at the user's side based on instruction transmitted on the control channel. This method requires an established connection between BS and MS, which is not applicable for some scenarios (e.g. when MS first logs into the network), and additional signaling, which reduces system's throughput. In [1, 2], a multiple CFOs estimation and compensation algorithm is introduced based on subspace method. This scheme works only with interleaved subcarrier allocation. In [4, 5, 7], ICI cancellation schemes in frequency-domain are proposed, where additional processing block besides the Fast Fourier Transform (FFT) is required at BS to compensate for ICI due to CFOs.

In this paper, we propose a simple but effective scheme to mitigate effects of multiple CFOs coming from multiple users in the uplink of OFDMA systems. Based on multiple OFDMA-demodulator architecture, the scheme is able to correct and compensate for the ICI at the BS's side. As a result, no additional signalling is needed and terminal simplicity is allowed. It can work with both contiguous and interleaved subcarrier allocations, and does not require additional processing block, except the FFT.

This paper is organized as follows: The system model of uplink OFDMA is presented in Section II. Section III discusses our proposal in details. Simulation results are reported in Section IV, and conclusions are drawn in Section V.

II. SYSTEM MODEL

Let's consider an OFDMA system using a FFT of size N. At the s^{th} symbol, the u^{th} user is given an independent set of subcarriers, denoted as $\Delta_{u,s}$. The transmitted information of the u^{th} user at the k^{th} subcarrier, therefore, can be expressed as:

$$\mathbf{X}_{u,s}[k] = \begin{cases} d_{u,s,k} & k \in \Delta_{u,s} \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

where $d_{u,s,k}$ is the data belonging to the u^{th} user at the k^{th} subcarrier of the s^{th} symbol. This information is modulated by the Inverse Fast Fourier Transform (IFFT) operation and sent through a frequency-selective fading channel with the Channel Transfer Function (CTF) at the k^{th} subcarrier is given by:

$$\mathbf{H}_{u,s}[k] = \sum_{l=0}^{L-1} h_{u,l}[s]\, e^{-j2\pi \frac{k}{T_u}\tau_{u,l}} \tag{2}$$

where $h_{u,l}[s]$ and $\tau_{u,l}$ are the complex gain and time delay of the l^{th} multipath component for the u^{th} user at the s^{th} symbol, respectively, and T_u is the OFDM symbol duration without guard interval. The channel is assumed to be static for the

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duration of one OFDM symbol, and the path gain coefficients for each path contribution are assumed to be uncorrelated.

Assume that each user observes independent timing-offset δt_u and frequency-offset δf_u, which are constant during the observation period. Assume that the Cyclic Prefix (CP) is long enough to accommodate both the maximum timing-offset and the channel delay spread, so that there is no influence of the adjacent OFDM symbols transmitted. The received information on the k^{th} subcarrier of the u^{th} user then can be written as:

$$\begin{aligned} z_{u,s,k} = {} & \mathbf{H}_{u,s}\,[k]\,\mathbf{X}_{u,s}[k] e^{-j2\pi\frac{k}{N}\epsilon t_u} e^{j2\pi\epsilon f_u \frac{(sN_s+N_g)}{N}} \mathcal{C}(\epsilon t_u) \\ & + ICI_{u,s,k,self} + ICI_{u,s,k,cross} + v_{s,k} \qquad (3) \end{aligned}$$

where $\epsilon t_u = \frac{\delta t_u}{\Delta t}$ and $\epsilon f_u = \frac{\delta f_u}{\Delta f}$ are normalized timing- and frequency-offset, respectively; N_g is number of guard interval samples; $N_s = N + N_g$ is the total number samples in one OFDM symbol duration; $\mathcal{C}(\phi) = \frac{\sin \pi\phi}{N \sin \pi\phi/N} e^{j\pi\phi(N-1)/N}$ denotes periodic sinc-function [6]; $v_{s,k} = \sum_{n=0}^{N-1} n_{s,n} e^{-j2\pi\frac{n}{N}k}$ is the Additive White Gaussian Noise (AWGN) contribution at the k^{th} subcarrier of the output of OFDM demodulator; and $n_{s,n}$ is the complex baseband AWGN sample at the input of the OFDMA receiver.

$ICI_{u,s,k,self}$ and $ICI_{u,s,k,cross}$ are self- and cross-interference terms, i.e. ICI due to other subcarriers of the same user and ICI due to subcarriers of other users in the system, respectively:

$$\begin{aligned} ICI_{u,s,k,self} = & \sum_{k''\in\Delta_{u,s};k''\neq k} \mathbf{H}_{u,s}\,[k'']\,\mathbf{X}_{u,s}[k''] e^{-j2\pi\frac{k''}{N}\epsilon t_u} \\ & \times e^{j2\pi\epsilon f_u \frac{(sN_s+N_g)}{N}} \mathcal{C}(k''-k+\epsilon f_u) \qquad (4) \end{aligned}$$

$$\begin{aligned} ICI_{u,s,k,cross} = & \sum_{u'=0;u'\neq u}^{U-1} \sum_{k'\in\Delta_{u',s}} \mathbf{H}_{u',s}\,[k']\,\mathbf{X}_{u',s}[k'] \\ & \times e^{-j2\pi\frac{k'}{N}\epsilon t_{u'}} e^{j2\pi\epsilon f_{u'} \frac{(sN_s+N_g)}{N}} \\ & \times \mathcal{C}(k'-k+\epsilon f_{u'}) \qquad (5) \end{aligned}$$

From (3), (4) and (5), it is clear that a non-zero CFO would cause: (a) An attenuation of the received signal (since $\mathcal{C}(\epsilon t_u)$ is always less than one if ϵt_u is non-zero); (b) Self-interference and (c) Cross-interference. The conventional OFDMA receiver architecture, which uses only one OFDM demodulator, is unable to cope with multiple CFOs scenario. The OFDM demodulator can only be adapted to one user at a time, i.e. correction of one user's CFO would misalign all the others [9].

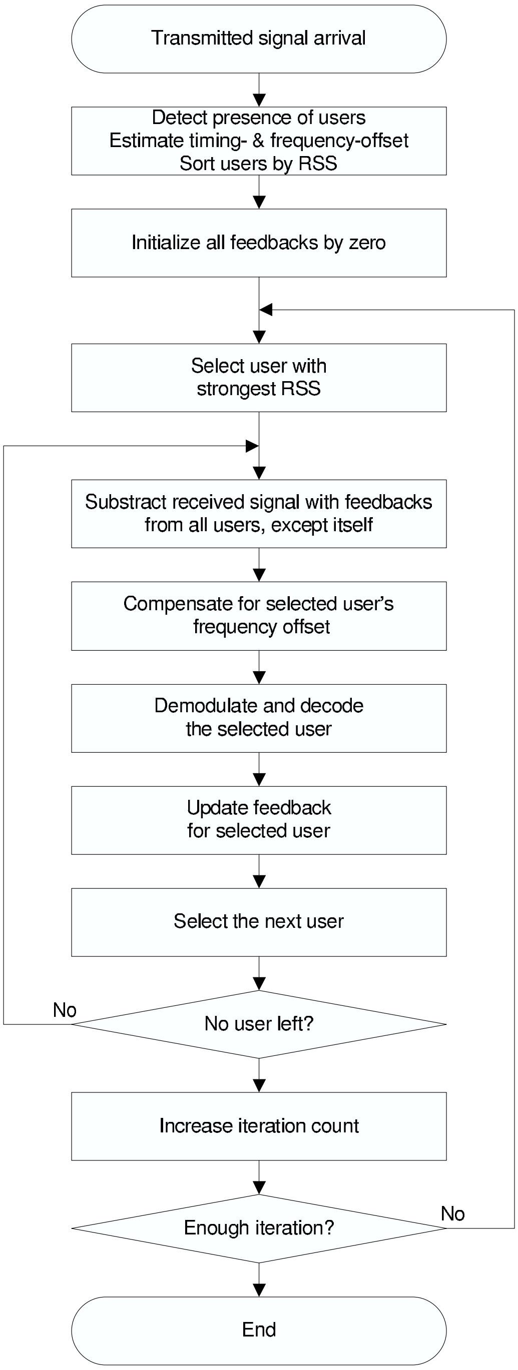

Figure 1: Implementation flowchart

III. OUR PROPOSAL FOR UPLINK OFDMA

Our proposed algorithm and receiver architectures for uplink OFDMA are illustrated in Fig. 1 and 2, respectively. The algorithm is applicable for both receiver architectures, Multi-User Interference Cancellation Scheme 1 (MUICS1) and Multi-User

Interference Cancellation Scheme 2 (MUICS2), and can be described briefly as follows: First, the BS detects the presence of users, estimate timing-, frequency-offset and Received Signal Strength (RSS) for each user. There are various methods to accomplish these tasks, which are not in the scope of this paper. For example, the user-specific CFO can be estimated by maximum-likelihood method as described in [4]. Second, the detected users are sorted by their RSS, and the BS will demodulate the user with strongest RSS first. In this way, the BS is likely to get the most accurate estimation out of this user, and thus has better chance to remove cross-interference due to this user. The output of the demodulation will be used to produce feedback that allows BS to remove the MUI caused by this user for other users. Which portion of the demodulation output is used to produce the feedback dictates the difference between MUICS1 and MUICS2. The same process is repeated for all other users, and the whole process can be repeated for several iterations to remove the MUI for all users. The proposed algorithm can be seen as Successive Interference Cancellation (SIC) implementation, but Parallel Interference Cancellation (PIC) can also be realized if we move the block "Substract received signal with feedbacks from all users, except itself" out of user selection loop.

Analytical details of the algorithm can be explained as follows: After CFO compensation, the output of the OFDM demodulator of the u^{th} user is given by:

$$\begin{aligned} z_{u,s,k}^{mDFT} &= \mathbf{H}_{u,s}\,[k]\,\mathbf{X}_{u,s}[k]e^{-j2\pi\frac{k}{N}\epsilon t_u} \\ &\quad + ICI_{u,s,k,cross}^{mDFT} + v_{u,s,k}^{mDFT} \end{aligned} \tag{6}$$

where $v_{u,s,k}^{mDFT} = \sum_{n=0}^{N-1} n_{s,n} e^{-j2\pi\frac{n}{N}k} e^{-j2\pi\epsilon f_u \frac{(sN_s+N_g+n)}{N}}$ is the frequency-shifted version of the AWGN contribution at the k^{th} subcarrier. The ICI term due to other users is:

$$\begin{aligned} ICI_{u,s,k,cross}^{mDFT} = & \sum_{u'=0;u'\neq u}^{U-1} \sum_{k'\in\Delta_{u',s}} \mathbf{H}_{u',s}\,[k']\,\mathbf{X}_{u',s}[k'] \\ & \times e^{-j2\pi\frac{k'}{N}\epsilon t_{u'}} e^{j2\pi\epsilon f_{u'}^{mDFT}\frac{(sN_s+N_g)}{N}} \\ & \times \mathcal{C}(k'-k+\epsilon f_{u'}^{mDFT}) \end{aligned} \tag{7}$$

in which $\epsilon f_{u'}^{mDFT} = \epsilon f_{u'} - \epsilon f_u$ is the relative CFO between the u^{th} and u'^{th} user. It is clear that, for the desired u^{th} user, the attenuation factor and the self-interference have disappeared, provided that the CFO ϵf_u is estimated correctly. However, the cross-interference term is still present.

In (7), we can see that the cross-interference term is a deterministic function, depending on the transmitted data symbols, channel frequency response and timing- and frequency-offset of the other users. Therefore, it is possible to cancel this ICI term, if all other parameters are known. Fortunately, this is the case in the cellular's uplink: The BS does estimate those parameters for each user, which facilitates the MUI cancellation schemes.

Since the u^{th} user has already been demodulated, the BS can demodulate the u'^{th} user with the knowledge of the u^{th} user. To make the analysis simpler, we assume that there are only two users in the system. In MUICS1, the time-domain contribution of the u^{th} user can be found by performing IFFT on its frequency-domain output and re-insert the previously-corrected CFO (ϵf_u):

$$\begin{aligned} \mathbf{x}_{u,s}^{MUICS1} &= \{x_{u,s,n}^{MUICS1} | n = 0, 1, \ldots, N-1\} \\ x_{u,s,n}^{MUICS1} &= \frac{1}{N} \sum_{k\in\Delta_{u,s}} z_{u,s,k}^{mDFT} e^{j2\pi\frac{nk}{N}} e^{j2\pi\epsilon f_u \frac{(sN_s+N_g+n)}{N}} \end{aligned} \tag{8}$$

Subtracting $\mathbf{x}_{u,s}^{MUICS1}$ (the feedback) from received signal in time-domain and performing OFDM demodulation for the u'^{th} user, we obtain:

$$z_{u',s,k'}^{MUICS1} = H_{u',s}[k']\mathbf{X}_{u',s}[k']e^{-j2\pi\frac{k'}{N}\epsilon t_{u'}} + v_{u',s,k'}^{MUICS1} \tag{9}$$

in which:

$$\begin{aligned} v_{u',s,k'}^{MUICS1} = & v_{u',s,k'}^{mDFT} \\ & - \sum_{k\in\Delta_{u,s}} \sum_{k''\in\Delta_{u',s}} H_{u',s}[k'']\mathbf{X}_{u',s}[k'']e^{-j2\pi\frac{k''}{N}\epsilon t_{u'}} \\ & \times \mathcal{C}(k''-k+\epsilon f_{u'})\mathcal{C}(k-k'+\epsilon f_u) \\ & - \sum_{k\in\Delta_{u,s}} v_{u,s,k}^{mDFT} e^{j2\pi\epsilon f_u^{mDFT}\frac{(sN_s+N_g)}{N}} \\ & \times \mathcal{C}(k-k'+\epsilon f_u^{mDFT}) \end{aligned} \tag{10}$$

is the noise and ICI terms resulted from MUICS1 and $\epsilon f_u^{mDFT} = -\epsilon f_{u'}^{mDFT}$.

As we can see from (9) and (10), the cross-interference term, $ICI_{u',s,k',cross}^{mDFT}$, has been successfully removed and two additional noise terms are introduced at the output of the OFDM demodulator for the u'^{th} user. These two additional noise terms can also be removed, if MUICS2 is used.

In MUICS2, instead of feeding the output of the OFDM demodulator of the u^{th} user back, we can choose to send only the estimated channel $\hat{H}_{u,s}[k]$ and data symbols $\hat{X}_{u,s}[k]$ back, i.e:

$$\begin{aligned} \mathbf{x}_{u,s}^{MUICS2} &= \{x_{u,s,n}^{MUICS2} | n = 0, 1, \ldots, N-1\} \\ x_{u,s,n}^{MUICS2} &= \frac{1}{N} \sum_{k\in\Delta_{u,s}} \hat{H}_{u,s}[k]\hat{X}_{u,s}[k]e^{j2\pi\frac{nk}{N}} \\ &\quad \times e^{j2\pi\epsilon f_u \frac{(sN_s+N_g+n)}{N}} \end{aligned} \tag{11}$$

Similar to MUICS1, subtracting $\mathbf{x}_{u,s}^{MUICS2}$ from received signal and performing OFDM demodulation for the u'^{th} user, we have:

$$\begin{aligned} z_{u',s,k'}^{MUICS2} = & H_{u',s}[k']\mathbf{X}_{u',s}[k']e^{-j2\pi\frac{k'}{N}\epsilon t_{u'}} + v_{u',s,k'}^{mDFT} \\ & + \sum_{k\in\Delta_{u,s}} (H_{u,s}[k]\mathbf{X}_{u,s}[k]e^{-j2\pi\frac{k}{N}\epsilon t_u} \\ & - \hat{H}_{u,s}[k]\hat{X}_{u,s}[k]) \\ & \times e^{j2\pi\epsilon f_u^{mDFT}\frac{(sN_s+N_g)}{N}} \mathcal{C}(k-k'+\epsilon f_u^{mDFT}) \end{aligned} \tag{12}$$

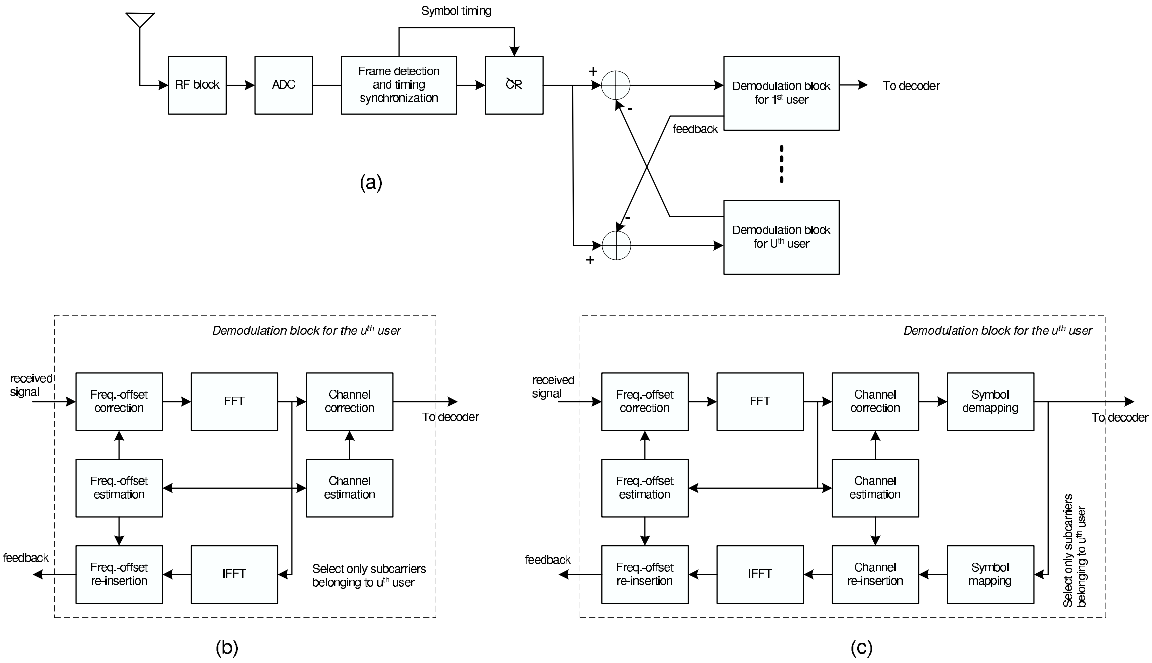

Figure 2: Multi-user Interference Cancellation Schemes: (a) General receiver structure (b) Implementation of the demodulation block in MUICS1 (c) Implementation of the demodulation block in MUICS2

Table 1: System parameters

Parameter	Value
System bandwidth	40MHz
Number of subcarriers	1024
CP length	200 samples
Subcarrier allocation scheme	Contiguous and Interleaved
Modulation	Quadrature Phase Shift Keying (QPSK)
Channel coding	None
Channel model	Medbo’s wideband model E [8]
Number of iterations	4

If the estimation of channel and data symbols for the u^{th} user are correct, the third term in (12) will go to zero, leaving no cross-interference at the output of OFDM demodulator of the u'^{th} user. In order to achieve correct estimation of data symbols, channel coding can be applied in the MUICS2.

IV. NUMERICAL EVALUATION

Table 1 summarises the basic system parameters which are used in the simulation. We assume timing-offset, frequency-offset and channel response are perfectly estimated.

In Fig. 3 is the uncoded Bit Error Rate (BER) performance of the proposed scheme versus Signal to Noise Ratio (SNR). There are two users in the system with equal transmitting power and relative CFO of 20% of subcarrier spacing. In conventional OFDMA receiver, the cross-interference causes the irreducable error floor, which cannot be overcome by increasing the transmit power. This error floor is removed by applying MUICS1 or MUICS2.

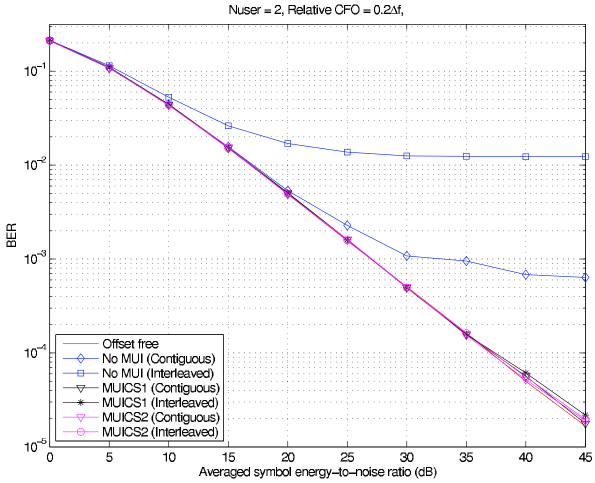

Figure 3: Uncoded BER performance versus SNR

Fig. 4 illustrates the uncoded BER performance of the schemes as a function of CFO. Again, there are two users in the system with equal transmitting power, and the SNR is 40dB. As we can see, the MUICS1 and MUICS2 schemes can handle large relative frequency offset with negligible performance degradation. This is because the effects of amplitude reduction, self- and cross-interference are successfully removed.

Since no channel coding is applied, performance of the MUICS2 scheme is not different from that of MUICS1. We

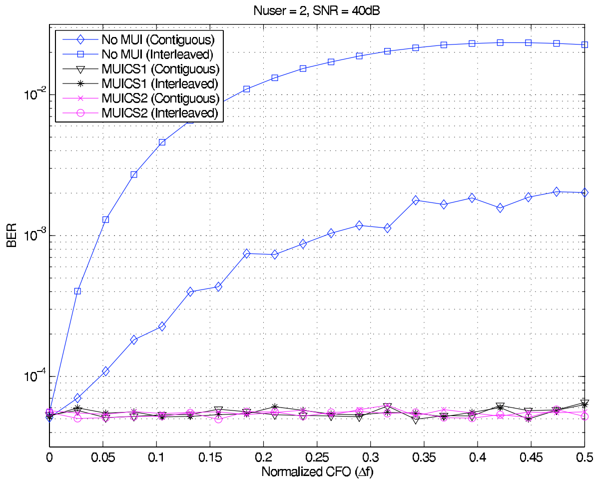

Figure 4: Uncoded BER performance versus relative CFO

would expect the MUICS2 performs better with channel coding, especially in scenarios with more users.

V. CONCLUSIONS

This paper has proposed novel MUI Cancellation Schemes, which are very effective against the effects of multiple CFOs in the uplink OFDMA. Numerical evaluation has shown that the schemes outperform the performance of the conventional OFDMA receiver, for both contiguous and interleaved subcarrier allocations. These schemes are especially useful in scenarios where BS cannot instruct users to adjust their CFO or implementation of such instruction is expensive (e.g. there is no feedback channel or low cost terminal does not have ability to adjust its frequency base accurately). They are compatible with current standard for MS using OFDMA technique, for example IEEE 802.16, since all changes are transparent for MS.

The proposed schemes introduced additional complexity, which can be justified by the fact that the complexity is added only to BS and the lower cost and faster operation of FFT processing chip. The schemes are relied on correct estimation of relative frequency offset, therefore it must be used in conjunction with a good method for frequency offset estimation.

In future, it could be interesting to investigate the performance of the schemes in scenarios where the number of users is greater than two, and when the estimation of CFO and channel is imperfect. It is also of interest to study the convergence property of these schemes.

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