Dynamic Fractional Frequency Reuse based on Interference Avoidance Request for Downlink OFDMA Cellular Networks *

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ABSTRACT

In this paper, we propose a dynamic fractional frequency reuse (DFFR) scheme, which is based on a interference avoidance request (IAR) mechanism, to suppress the inter-cell interference (ICI) for downlink OFDMA cellular networks. The key idea of the proposed scheme is that base stations (BSs) exchange IAR messages among each other, and then dynamically control the transmit power according to their received IAR messages. For the elastic data traffic, we combine the IAR mechanism with proportional fairness (PF) scheduling algorithm, to achieve good performances of both total cell throughput and cell edge user (CEU) throughput. Extensive system level simulations show that the proposed DFFR scheme outperforms the reference frequency reuse schemes in terms of the total cell throughput and CEU throughput. Furthermore, the proposed DFFR scheme requires no centralized controller, and the exchanged information among BSs is very little.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*wireless communication*

General Terms

Algorithms

Keywords

Inter-cell interference, frequency reuse, resource allocation, proportional fairness scheduling

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1. INTRODUCTION

To support high-speed wireless multimedia applications for the next generation wireless cellular networks, such as long term evolution (LTE), orthogonal frequency division multiplexing access (OFDMA) is proposed as a promising multiple access scheme [1]. In OFDMA cellular networks, intra-cell interference within a single cell is mostly eliminated due to the orthogonality of subcarriers. However, serious inter-cell interference (ICI) occurs when the frequency reuse factor equals to one, resulting in reducing system capacity, and substantially degrading the performance of cell edge users (CEUs). Thus, it is important to suppress ICI in OFDMA cellular networks.

Recently, a number of schemes have been proposed to discuss how to suppress ICI in OFDMA cellular networks. In the traditional Reuse 3 scheme [2, 3], the whole frequency band is equally separated for each set of 3 neighboring cells. In [4, 5, 6], the soft frequency reuse (SFR) scheme was proposed, in which the frequency reuse factor equals to one in the cell center region, but the frequency reuse factor equals to 3 or larger in the cell edge region. In [7], the softer frequency reuse (SerFR) scheme was proposed, in which user scheduling are more flexible than those of SFR schemes. However, the frequency reuse factor is static in all above frequency reuse schemes. In [8], ICI avoidance could be achieved via dynamic fractional frequency reuse, where each cell always performs a "selfish" optimization of the user assignments over its resource sets, to minimize the power consumption. It has been shown that the scheme proposed in [8] only support constant-bit-rate user traffic. In [9], a co-channel interference avoidance medium access control (CIA-MAC) scheme was proposed to improve the network throughput performance. For CIA-MAC, base stations, that are judged as severe interferers, are only allowed to transmit randomly and their transmissions are controlled over the variation of wireless channel states. However, the situation of multiple subbands and subchannels was not discussed in [9]. In [10], a centralized ICI avoidance scheme has been proposed, where each cell sends a request to the central controller, to keep interferers from using some chunks. The central controller processes such requests from all cells, and then blocks the usage of certain chunks for some cells in an optimal fashion.

In this paper, we propose a dynamic fractional frequency reuse (DFFR) scheme, which is based on interference avoidance request (IAR) mechanism to suppress ICI for downlink OFDMA cellular networks. The key idea of the DFFR scheme is that the BSs dynamically control their transmit power via an IAR mechanism. For the proposed IAR mechanism, CEUs send IAR messages to their serving BSs, to request their major interferers to reduce transmit power over certain subbands. Each BS receives IAR messages from CEUs and exchanges with other BSs, then it controls the transmit power according to its received IAR messages. As a result, the ICI is greatly reduced and efficient frequency reuse patterns are achieved dynamically for CEUs.

The main contributions of this paper are summarized as follows: The proposed DFFR scheme requires no centralized controller, and the exchanged information among BSs is very little. For the elastic data traffic, we combine the IAR mechanism with proportional fairness (PF) scheduling algorithm [11, 12], to achieve good performances of both total cell throughput and CEU throughput. Furthermore, the performance of the proposed DFFR scheme is compared with four reference frequency reuse schemes: Reuse 1 [2], Reuse 3 [2, 3], SFR [4, 5, 6], and SerFR [7], the results show the proposed DFFR scheme can achieve the best total cell throughput and CEU throughput simultaneously.

The rest of this paper is organized as follows. In Section II, we first introduce a typical OFDMA cellular network model under consideration, and then present the four reference frequency reuse schemes. In Section III, we give a detailed descriptions of the proposed DFFR scheme, which is based on the IAR mechanism. Simulation results and discussions are presented in Section IV. Finally, conclusions are drawn in Section V.

2. OFDMA CELLULAR NETWORK AND FREQUENCY REUSE SCHEMES

In this section, we first introduce a typical OFDMA cellular network model assumed in our study, and then we present four reference frequency reuse schemes.

2.1 OFDMA Cellular Network Model

We consider the downlink of a three-tier OFDMA cellular network consisted of J hexagonal cells, and $J = 19$ in this paper, as shown in Fig. 1. For each cell, one BS equipped with omnidirectional transmit antenna is at the center. Moreover, the whole frequency band is divided into N_S subbands and each user is allocated some subbands in each transmission time interval (TTI). Without loss of generality, we assume that cell 1 is the current considered cell, and there are N_U users supported simultaneously in cell 1. We assume that the channel status does not vary within each TTI, and the base station has perfect knowledge of instantaneous channel state information (CSI). By using adaptive modulation, at time t, the achievable data rate $r_{u,n}(t)$ for user u on subband n is calculated with instantaneous SINR $\rho_{u,n}$. For any subband n, the instantaneous SINR $\rho_{u,n}$ of user u supported in cell 1 is expressed as:

$$\rho_{u,n} = \frac{P_n \cdot h_{u,n}}{P_N + \sum_{j=2}^{J} P_{j,n} \cdot h_{j,u,n}}, \tag{1}$$

where P_n is the transmit power employed by BS 1 on subband n, $h_{u,n}$ is the instantaneous channel gain (including path loss, shadowing, and fast fading) from BS 1 to user u on subband n, P_N is the thermal noise power over the subband bandwidth, $P_{j,n}$ is the transmit power employed by interfering BS j on subband n, and $h_{j,u,n}$ is the instantaneous channel gain from interfering BS j to user u on subband n.

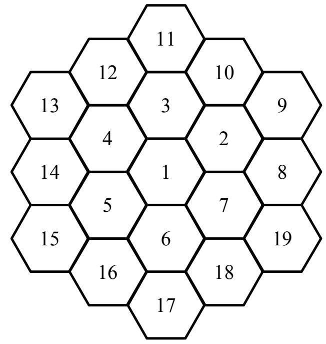

Figure 1: A typical OFDMA cellular network consisted of 19 hexagonal cells in three tiers.

The second part of the denominator in (1) is ICI, which is consisted of the received interference powers from neighboring cells. For a typical cellular network, ICI is the major limiting factor for the user SINR compared with the thermal noise.

2.2 Existing Frequency Reuse Schemes

To suppress ICI for downlink OFDMA cellular networks, some frequency reuse schemes have been proposed.

2.2.1 Reuse 1

In the reuse 1 scheme [2], the strongest ICI is observed, especially for CEUs. As a result, these CEUs are expected to have poor SINR, which greatly reduces their scheduling opportunities and throughput performance.

2.2.2 Reuse 3

The traditional Reuse 3 scheme in [2, 3] is a simple technique to suppress ICI, which divides the whole frequency band equally for each set of 3 neighboring cells. Due to the elimination of co-channel interferences from the neighboring cells, the Reuse 3 scheme leads to an improvement in SINR. However, due to the reduction in the available bandwidth, the total cell throughput decreases compared with that of Reuse 1.

2.2.3 SFR

In the SFR scheme [4, 5, 6], the frequency reuse factor equals to one in the cell central region, but the frequency reuse factor equals to 3 or larger in the cell edge region. On the other hand, a cell classifies its users into two categories: cell center user (CCU) and cell edge user (CEU) based on their locations within the cell. And the cell first assigns CEUs the frequency band with high power, then assigns CCUs the remaining frequency bands.

2.2.4 SerFR

In [7], the SerFR scheme is proposed to achieve higher frequency selective scheduling gains than SFR. In this scheme, user scheduling are more flexible than those of SFR schemes. The CEUs have a higher probability to be assigned with the frequency band with high power, while the CCUs have a higher probability to be assigned with the frequency band with low power. Compared with SFR, SerFR achieves a CEU performance gain at the cost of slight total cell throughput degradation.

3. DFFR BASED ON THE IAR MECHANISM

In this section, we first present overview of the proposed DFFR scheme, which is based on the IAR mechanism to suppress ICI. Then we combine the IAR mechanism with the conventional PF scheduling algorithm in resource allocation.

3.1 Overview of DFFR based on the IAR Mechanism

Since CEUs located near the handoff region are affected by co-channel interference severely, the cells should assign CEUs to some specially managed subbands, in which the co-channel interference from the neighboring cells are significantly reduced. The implementation of this idea is achieved via the proposed IAR mechanism.

In the proposed DFFR scheme, the whole frequency resources are divided into N_S subbands, which are classified into three categories: common subband (CSB), priority subband (PSB), and interference avoidance subband (IASB). For each cell, one group of subbands are CSBs, the other one group of subbands are PSBs, and the remaining subbands are IASBs. The CSBs of all the cells are the same, while the PSBs should be carefully planned to avoid using the same subbands as PSBs in neighboring cells.

All the CSBs and PSBs are transmitted with the maximum power P_{max}. The CSBs are used to measure the instantaneous SINR and major interference cells on nearby subbands. On the other hand, the transmit power on each IASB is dynamic and adjusted according to the IAR messages from neighboring cells. When a CEU is assigned to a PSB, we assume that the CEU could sense the strongest interfering BSs on this PSB, which can be achieved by identifying the unique pilot sequences of BSs. Then this CEU request the strong interfering BS to reduce $K\triangle$ dB transmit power by sending an IAR message, where K is the number of IARs in the IAR message. An IAR requests the corresponding BS to reduce transmit power on the corresponding IASB for $\triangle$ dB. When a BS receives an IAR message containing K IARs from a single BS, it has to reduce $K\triangle$ dB transmit power on its IASB specified by the IAR message. Note that a BS may receive multiple IAR messages for the same IASB from different BSs, in this case it reduces transmit power according to the IAR message with the maximum number of IARs. Due to the power control of neighboring cells on their IASBs, the co-channel interferences on the PSBs can be effectively reduced. Since the BSs only need to exchange a limited number of IAR messages, the signaling overhead is very little.

3.2 User Grouping

Before going to the details of resource allocation algorithm, a proper measure should be taken to determine whether a user is CEU or CCU. We assume that the average SINR γ_u of user u could be obtained at the terminal. Collecting the average SINR from all users, the network could determine an SINR threshold δ. A user with $\gamma_u < \delta$ is considered to be the CEU, while a user with $\gamma_u \geq \delta$ is considered to be the CCU. To allow severely interfered CEUs enjoy larger number of IARs, the number of IARs I_u enjoyed by CEU u could be set as a function of its average SINR. We equally divide all the users into Q levels according to their average SINR values, and the numbers of IARs enjoyed by each level of users are different. The average SINR value interval of level q users is $[\bar{\gamma}_{q-1},\bar{\gamma}_q]$, where $\bar{\gamma}_q$ is given as:

$$\bar{\gamma}_q = \begin{cases} -\infty, & q = 0 \\ g^{-1}(\frac{q}{Q}), & q = 1, 2, \ldots, Q-1, \\ +\infty, & q = Q \end{cases} \tag{2}$$

where $g(\gamma)$ is the cumulative density function (CDF) of users' average SINR γ, which is defined as:

$$g(\gamma) = P\{\gamma_u \leq \gamma\}. \tag{3}$$

For each CEU u, its average SINR γ_u is obtained from the measurement of SINR over all CSBs during a certain period of time. Then, its level q_u is identified according to γ_u. Finally, the number of IARs I_u enjoyed by user u is determined by q_u.

3.3 Resource Allocation

For elastic data traffic, we combine the IAR mechanism with proportional fairness (PF) scheduling algorithm in resource allocation. Based on the instantaneous channel gains of users, BSs allocate subbands and powers to them for each TTI. In the following, we describe steps of the proposed resource allocation algorithm. Each CEU sends CSI to its serving BS before scheduling, which includes subband channel gain of the serving BS and those of the major interfering BSs. Then, PSB allocation is performed in each cell independently. After that, BSs exchange the IAR messages and perform power control. Finally, CSBs and IASBs are allocated in each cell independently.

3.3.1 PSB Allocation

The following PSB allocation is performed in each cell independently. $U = \{1, 2, \ldots, N_U\}$ is the set of users, and N_U is the number of users in set U. $A_{PSB} = \{n|\text{subband } n \text{ is a PSB}\}$ is the set of PSBs, $BS_I = \{2, 3, \ldots, J\}$ is the set of major interfering BSs for current considered BS 1, and $P^{'}_{j,n}$ is the assumed transmit power employed by interfering BS j on subband n, considering the usage of IARs. For CEU u on subband n, $M^{'}_{j,u,n}$ is the assumed received interference power from interfering BS j, and $I_{j,u,n}$ is the number of IARs sent to interfering BS j.

The main part of the PSB allocation algorithm consists of a loop that iterates on the PSBs. Details are given in Algorithm 1. For PSB n, the achievable data rate $r'_{u,n}(t)$ for CEU u is estimated taking into account of the usage of I_u IARs. For CEU u, its I_u IARs are assumed to be optimally allocated to its interfering BSs as described in Algorithm 1. However, $r''_{u,n}(t)$ for CCU u is estimated without using IARs. Then the PF priority of each user on PSB n is calculated, and the PSB n is assigned to the user u^* with maximum PF priority. If user u^* is CEU, it sends an IAR message containing $I_{j,u^*,n}$ IARs to interfering BS j on subband n.

3.3.2 Power Control

Each BS identifies the list of IAR messages from CEUs and exchanges the list with other BSs. Then each BS controls the transmit power according to its received IAR messages. $A_{IASB} = \{n|\text{subband } n \text{ is a IASB}\}$ is the set of IASBs.

The main part of the power control algorithm consists of a loop that iterates on the IASBs. Details are given in Algorithm 2. For each IASB n, a BS may receive multiple

Algorithm 1 PSB Allocation

$T_u(t) = \frac{T_u(t-1)\cdot(T-1)}{T}, \forall u \in U$
for each subband $n \in A_{PSB}$ **do**
  for each user $u \in U$ **do**
    if user $u \in$ CEU **then**
      $P^{'}_{j,n} = P_{max}$, $M^{'}_{j,u,n} = P^{'}_{j,n} h_{j,u,n}$, $I_{j,u,n} = 0, \forall j \in BS_I$
      for IAR $i = 1$ to I_u **do**
        //find the strongest interfering BS j^*:
        $j^* = \arg\max_{j\in BS_I} M^{'}_{j,u,n}$
        $I_{j^*,u,n} = I_{j^*,u,n} + 1$
        $P^{'}_{j^*,n} = P^{'}_{j^*,n} - \triangle$ dB
        $M^{'}_{j^*,u,n} = P^{'}_{j^*,n} h_{j^*,u,n}$
      end for
      $\rho^{'}_{u,n} = \frac{P_{max}\cdot h_{u,n}}{P_N + \sum_{j=2}^{J} P^{'}_{j,n}\cdot h_{j,u,n}}$
      Based on $\rho^{'}_{u,n}$, $r^{'}_{u,n}(t)$ is calculated via a lookup table.
      $p_{u,n}(t) = \frac{r^{'}_{u,n}(t)}{T_u(t)}$
    else
      $\rho^{''}_{u,n} = \frac{P_{max}\cdot h_{u,n}}{P_N + \sum_{j=2}^{J} P_{max}\cdot h_{j,u,n}}$
      Based on $\rho^{''}_{u,n}$, $r^{''}_{u,n}(t)$ is calculated via a lookup table.
      $p_{u,n}(t) = \frac{r^{''}_{u,n}(t)}{T_u(t)}$
    end if
  end for
  $u^* = \arg\max_{u\in U} p_{u,n}(t)$, $T_{u^*}(t) = \frac{T_{u^*}(t)\cdot T + r_{u^*,n}(t)}{T}$
  if user $u^* \in$ CEU and $I_{j,u^*,n} \neq 0$ **then**
    An IAR message containing $I_{j,u^*,n}$ IARs is sent to interfering BS j on subband n.
  end if
end for

IAR messages for the same IASB n from different BSs, in this case it reduces $I_n\triangle$ dB transmit power on IASB n, where I_n is the maximum number of IARs among these IAR messages.

After all the IAR messages are correctly received and executed by each BS, the corresponding power control is finished. For the PSBs of each cell, since the major interfering BSs reduce the transmit power on their IASBs, the co-channel interference from the neighboring cells are greatly reduced. Thus, the power control generates efficient frequency reuse patterns for CEUs, which improves their throughput performance. In the following, each BS allocates the remaining CSBs and IASBs to users.

3.3.3 CSB and IASB Allocation

Algorithm 2 Power Control

for each subband $n \in A_{IASB}$ **do**
  Find out the number of IARs $I_{n,j}$ on IASB n from BS j, $\forall j \in BS_I$.
  //find out the maximum number of IARs on IASB n:
  $I_n = \max_{j\in BS_I} I_{n,j}$
  //reduces $I_n\triangle$ dB transmit power on IASB n:
  $P_n = P_{max} - I_n\triangle$ dB
end for

Algorithm 3 CSB and IASB Allocation

for each subband $n \in A_{rest}$ **do**
  for each user $u \in U$ **do**
    //the current instantaneous SINR $\rho_{u,n}$ of user u is computed as:
    $\rho_{u,n} = \frac{P_n\cdot h_{u,n}}{P_N + \sum_{j=2}^{J} P_{j,n}\cdot h_{j,u,n}}$
    where P_n is the current transmit power employed by BS 1 on subband n, $P_{j,n}$ is the current transmit power employed by interfering BS j on subband n.
    Based on $\rho_{u,n}$, $r_{u,n}(t)$ is calculated via a lookup table.
    $p_{u,n}(t) = \frac{r_{u,n}(t)}{T_u(t)}$
  end for
  $u^* = \arg\max_{u\in U} p_{u,n}(t)$, $T_{u^*}(t) = \frac{T_{u^*}(t)\cdot T + r_{u^*,n}(t)}{T}$
end for

The following CSB and IASB allocation is performed in each cell independently. $A_{CSB} = \{n|\text{subband } n \text{ is a CSB}\}$ is the set of CSBs, and $A_{rest} = A_{CSB} \cup A_{IASB}$, which is the union of set A_{CSB} and set A_{IASB}.

The main part of the CSB and IASB allocation algorithm consists of a loop that iterates on the remaining subbands. Details are given in Algorithm 3. For each remaining subband n, the PF priority of each user is calculated according to the conventional PF scheduling algorithm. Then the subband n is assigned to the user u^* with maximum PF priority.

4. SIMULATION RESULTS

In this section, we first describe the simulation parameters employed in this paper. Then the performance of the proposed DFFR scheme is compared with four existing frequency reuse schemes: Reuse 1, Reuse 3, SFR, and SerFR. All these schemes use the PF algorithm for subbands allocation.

4.1 Simulation Parameters

A total of 21 cell sites are considered in the simulation, and the inter-site distance is 1 km. To accurately reflect the influence of multicell interference, the cell layout is simulated with wrap-around method, where the 21 cell sites are repeated in the cellular network. At each TTI clock (10 ms), scheduling is performed in each cell independently.

The total bandwidth (5 MHz) is divided into 32 subbands, and there are 32 users randomly distributed in each cell. For the simplicity of simulations, a full buffer elastic traffic model is assumed for each user. The wireless channel is modeled as 2-path frequency-selective Rayleigh fading channel, and each path suffers from independent fading. User speed is assumed to be 3 km/h.

In Reuse 1, all the cells reuse the 32 subbands. In Reuse 3, 10 subbands are allocated to each cell of 3 neighboring cells, while the remaining 2 subbands are reuse in all the cells. All these subbands in Reuse 1 and Reuse 3 are transmitted with maximum power P_{max}. However, in SFR and SerFR, only 12 subbands are transmitted with maximum power P_{max}, and the remaining 20 subbands are transmitted with a reduced power $P_L = P_{max}/10$ (SFR and SerFR achieves best performance with these parameters by simulation). The high power subbands and low power subbands are placed in an interleaved manner for frequency diversity gains.

In DFFR, the numbers of subbands dedicated to CSBs

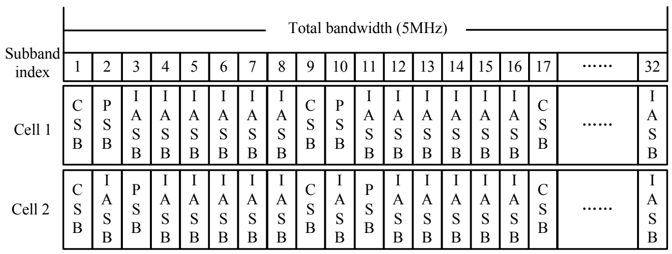

Figure 2: Subbands planning for the proposed DFFR scheme.

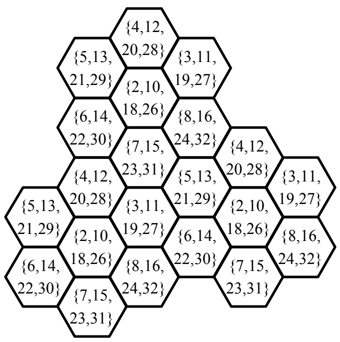

Figure 3: PSBs planning for a layout of 21 cells.

and PSBs are both 4, and the remaining 24 subbands are IASBs. The subbands of each group are placed in an interleaved manner. In this simulation, we adopt frequency reuse factor of 7 for PSBs, Fig. 2 shows the subbands planning for cell 1-2, and Fig. 3 shows the PSBs planning for a layout of 21 cells. On each PSB, the level $q-1$ user enjoys more m IARs than level q user, and the level 1 user (with worst average SINR) enjoys I_{max} IARs at most. Therefore, for user u, the number of IARs is $I_u = \max\{0, I_{max}-(q_u-1)m\}$, where q_u is the level of user u. For all the following simulations we set $I_{max} = 35$, $m = 8$.

The other system simulation parameters are listed in Table 1.

Table 1: Simulation Parameters.

Carrier frequency	2GHz
Distance-dependent path loss	$L = 128.1 + 37.6\log_{10}(R)$, R in kilometers
Lognormal Shadowing	log normal fading with 0 mean, 8dB standard deviation
Total BS transmit power	43dBm
Channel estimation	perfect
UE Noise Figure	9dB
White noise power density	-174dBm/Hz
Modulation	B/Q-PSK, 16/64-QAM
Cell edge threshold	$\delta = 5$dB
Observation window length of the average data rate	$T = 10$TTIs
$\triangle$dB	5dB
User levels	$Q = 10$

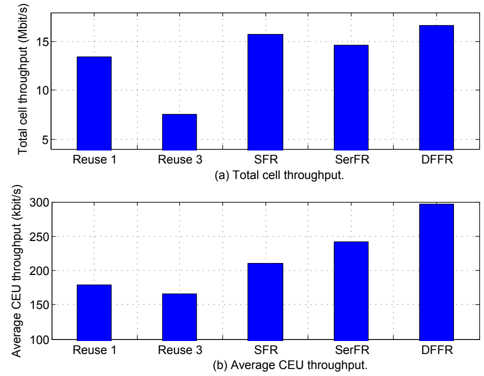

Figure 4: Throughput performance for all the frequency reuse schemes.

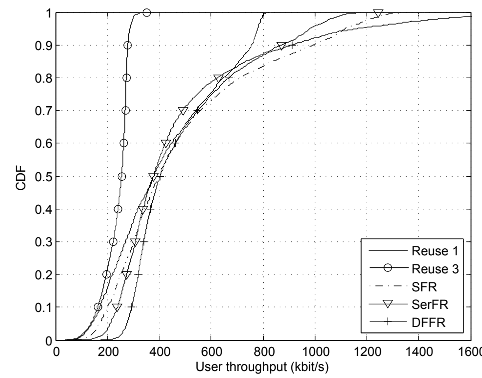

Figure 5: CDF of user throughput.

4.2 Simulation Results

Fig. 4 (a) shows the total cell throughput for all the frequency reuse schemes. Due to only one third of the available frequency resources for each cell, Reuse 3 shows the worst cell throughput of 7.58 Mbit/s. On the other hand, Reuse 1, SFR, and SerFR use the whole frequency resources, such that they show better throughput performance of 13.48 Mbit/s, 15.74 Mbit/s, and 14.66 Mbit/s, respectively. The proposed DFFR scheme performs better than all the reference schemes, and achieves 23.8% more throughput than Reuse 1. We plot in Fig. 4 (b) the average CEU throughput (the average throughput of the 25% worst users) for all the frequency reuse schemes. Due to the severe ICI for CEUs in Reuse 1 and the reduction of the available bandwidth in Reuse 3, they show very poor average CEU throughput of 178.85kbit/s and 166.06kbit/s, respectively. Compared with SFR, SerFR achieves better CEU throughput performance at the cost of the total cell throughput degradation. On the contrast, the DFFR scheme achieves not only the best total cell throughput, but also the best average CEU throughput. It achieves average CEU throughput increase by 65.6% compared with that of Reuse 1.

Fig. 5 presents the CDF curve of user throughput. The 5-percentile throughput is another measure of CEU performance. It is obvious that DFFR performs best at the 5-percentile throughput, with the gain of 101.7% compared with that of Reuse 1.

In Fig. 6, plot of user throughput vs. average SINR is

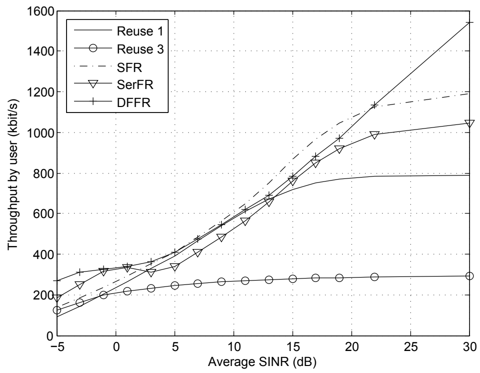

Figure 6: User throughput vs. average SINR.

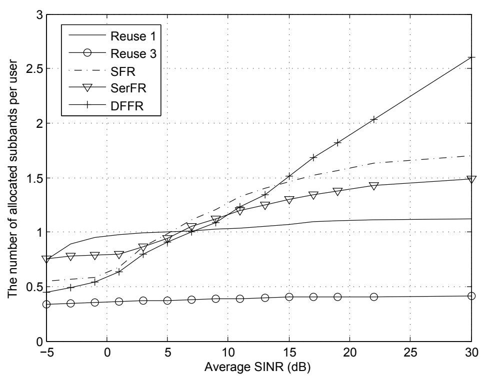

Figure 7: The number of allocated subbands per user vs. average SINR.

presented. It is observed that the user throughput is poor at all SINR region in Reuse 3. The throughput in Reuse 1 drops at the low SINR region, which means that Reuse 1 gains higher total cell throughput by sacrificing CEU throughput. We also see that SFR, SerFR, and DFFR all tend to improve the CEU throughput. Moreover, at both the low and high SINR region, the DFFR scheme shows the best performance.

In Fig. 7, we count the number of allocated subbands per user vs. average SINR. From the figure, we find two interesting phenomenons from the curve of DFFR: First, although the curve drops at the low SINR region, the throughput performance of low SINR users is actually increased, as shown in Fig. 6. This phenomenon demonstrates that DFFR effectively reduces the ICI. Second, the number of allocated subbands keeps rising at the high SINR region, which compensates the loss of high SINR users in power control, and improves their throughput performance, as shown in Fig. 6.

5. CONCLUSIONS

In this paper, we proposed a novel DFFR scheme, which is based on IAR mechanism, to suppress ICI for downlink OFDMA cellular networks. The proposed DFFR scheme requires no centralized controller, and the exchanged information among BSs is very little. Moreover, we combined the IAR mechanism with PF algorithm to support elastic data traffic. Extensive simulation results verified that the proposed DFFR scheme can achieve the best performances in terms of the total cell throughput and CEU throughput.

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