ADAPTIVE INTER-CELL INTERFERENCE MANAGEMENT FOR DOWNLINK FH-OFDMA SYSTEMS

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***Abstract*— For a cellular system, the system throughput as well as the throughput at a cell edge are among the most important evaluation measures for the requirements on the system performance. Several inter-cell interference mitigation techniques have been proposed to meet the cell-edge users' needs in downlink. Each interference mitigation scheme has been found that they have pros and cons at the same time. In this paper, an adaptive inter-cell interference management scheme is proposed for an LDPC-coded FH-OFDMA system to combat the inter-cell interference in downlink cellular environment. Based on the knowledge on other cells that we can utilize without dynamic cooperation between cells, different decoding methods can be applied to maximize the performance for the cell-edge users. It is shown that a significant gain can be obtained, especially at the cell boundary using the proposed scheme.**

***Keywords*— Interference, FH-OFDMA, Adaptive Decoding.**

1. INTRODUCTION

In modern wireless cellular communication systems, the system throughput as well as the throughput at a cell edge are among the most important evaluation measures for the requirements on the system performance [1]. Among many candidates on the multiple access schemes, frequency hopping orthogonal frequency division multiple access (FH-OFDMA) has been considered as one of the promising packet-based transmission techniques because FH-OFDMA can easily deal with the frequency selective fading channel and provide not only inner-cell orthogonality but also inter-cell interference (ICI) averaging effect. Thus it enables us to construct a cellular network with a frequency reuse factor equal to one [2]. However, the ICI averaging effect would not work properly in case that there exist interferers with differently allocated power loading in adjacent cells, which makes the ICI pattern highly non-uniform [3]. Therefore, it is very important to manage such non-uniform ICI, especially at cell edge.

Several ICI mitigation techniques have been proposed to provide reliable communication to cell-edge users. Traditional frequency reuse schemes, such as a reuse factor 3 deployment, can significantly reduce the average ICI. However, it sacrifices accessible frequency resource in each cell in order to manage the interference levels so that the overall system capacity is quite limited. Another method proposed to handle the ICI is the coordinated symbol-repetition scheme [4]. In this method, a repeated symbol mapping in the frequency domain is coordinated to be identical among adjacent cells. Then a UE can perform interference cancellation by using a minimum mean square error (MMSE) receiver in the frequency domain. This method can mitigate the ICI and increase the number of allowable interferers. But this scheme also needs additional resource due to the repetition, which ends up with limiting the system performance as well.

As an advanced version of the traditional frequency reuse scheme, two frequency reuse schemes have been proposed. One is the partial frequency reuse (PFR) scheme [5], and the other is the soft frequency reuse (SFR) scheme [6]. The PFR scheme partitions the whole frequency into two parts, a part with reuse factor 1 and the other with reuse factor less than 1. The reuse factor 1 part is used only by inner cell users and the other part can be used by cell edge users. This scheme greatly solves the limitation of the traditional frequency reuse scheme. However, there still exists inefficiency due to the part for the cell-edge users. In the SFR scheme, a part of the whole frequency is reserved for the cell edge users and is kept being orthogonal among adjacent cells. The remaining frequency band can be used only by inner cell users for each cell. The transmission power can be amplified on the reserved band for the cell-edge users and inner cell users can also use this reserved frequency band. Therefore, the SFR scheme can achieve the reuse factor of 1. But, both the PFR and the SFR schemes need a strict cell planning, which is very hard for a practical system [7]. If an irregular cell pattern is given, such frequency reuse schemes requiring a strict cell planning would lead to an inefficient use of the spectrum.

In [3], a soft channel reuse (SCR) scheme using an erasure decoding (ED) method with downlink power control was proposed to handle the non-uniform ICI for downlink FH-OFDMA systems. In this scheme, no strict cell planning is required due to its subchannel structure. It considered a multi-cellular downlink OFDMA system where a power control is performed such that a base station (BS) can use full power for up to a pre-determined number of subchannels allocated to cell-edge users while the rest of power is used for the subchannels allocated to inner-cell users. So all frequency resources can be utilized in each cell regardless of the cell shape. By erasing highly interfered symbols, it was shown that partially interfered signals can be effectively decoded without any prior knowledge on ICI. However, the ED method is only applicable to the case where a few subchannels are allowed for the outer cell region such that ICI is concentrated to a small fraction of subcarriers in the subchannel. As the number of cell edge users increases and demands more subchannels, the performance of the ED scheme is deteriorated.

In this paper, we propose an adaptive ICI management scheme for downlink FH-OFDMA systems using different

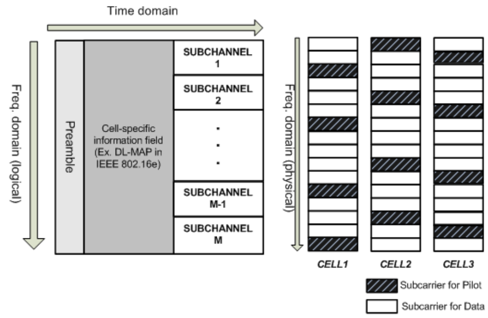

Figure 1. System Model

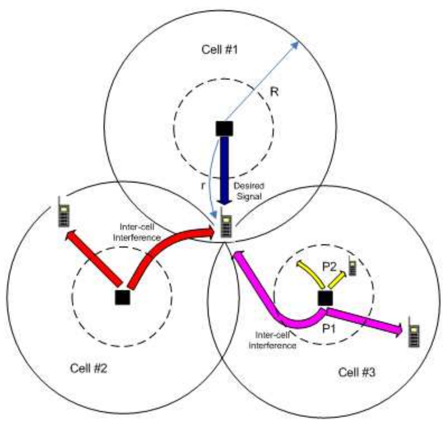

Figure 2. Interference Model

decoding methods in order to overcome the disadvantage of the SCR scheme using ED. By applying different ICI mitigation methods adaptively, the allowable number of channels for the cell-edge users is increased.

2. System Model

In this paper, we consider a packet-based downlink FH-OFDMA in a multi-cellular environment. Fig. 1 shows the system model that we are interested in. A slot consists of a cell-specific information field and *M* data subchannels. Here, *M* is the number of subchannels in a slot. Also the cell-specific information field contains the power information of each subchannel in the cell as well as other parameters. The UEs are assumed to be able to decode two or more cell-specific information signals coming from BSs including the serving BS. For better reception of this signal at cell-edge, a frequency reuse scheme is applied so that no ICI appears among adjacent cells on the cell-specific information field. Also, a common pilot channel may have a frequency reuse factor less than 1 so that robust channel estimation can be performed. We assumed that each data subchannel is well distributed over the time and the frequency domains such that each subchannel in a cell is evenly collided with all subchannels in a different cell.

Fig. 2 describes the interference model in a downlink FH-OFDMA system. A user of interest is located at the cell edge of cell 1, and several interferers exist in cell 2 and cell 3. We assume that each cell is divided into two regions: an inner region and an outer region. To effectively manage the interference problem, we put a restriction on the maximum number of data channels assigned to outer region users, which is denoted as *D* throughout this paper. Once the number of data channels for the outer region users is decided, the rest of the data channels is assumed to be assigned to the users in the inner region of the cell so that we can keep the frequency reuse factor of the data channel to be one. We assume that there are two kinds of maximum transmit power for the inner region users and the outer region users, P_1 and P_2, respectively. Since the maximum transmit power P_1 for the inner region users is much smaller than the maximum transmit power P_2 for the cell-edge users, the interference to the user of interest mostly comes from the subchannels allocated to cell-edge users in adjacent cells.

For a channel coding, a low-density parity-check code (LDPC) is used. A data packet of size *K* is encoded and outputs (c_k) is of length *N*. The output bits are mapped into the modulated symbols (x_l) of length $L = log_Q N$, where *Q* is the modulation order. Then, the symbols are put together with pilot symbols according to the slot configuration with OFDM modulation. For the UE of interest in the $i^{\underline{th}}$ cell, the received symbols of the assigned data channel can be written as

$$r_l = \sqrt{P_{i,l}\alpha_{i,l}} h_{i,l} x_{i,l} + \Sigma_{j=0,j\neq i}^{N_{cells}-1} \sqrt{P_{j,l}\alpha_{j,l}} h_{j,l} x_{j,l} + w_l, 0 \leq l \leq L-1 \quad (1)$$

where $P_{i,l}$, $\alpha_{i,l}$, $h_{i,l}$ and $x_{i,l}$ denote the transmit power, the path loss from large-scale fading, the multipath channel gain, and the modulated symbol on the $l^{\underline{th}}$ subcarrier from the BS of the $i^{\underline{th}}$ cell to the UE of interest, respectively. Also, N_{cells} denotes the total number of cells in the system, w_l is the additive Gaussian noise with variance σ_n^2, and *L* is the total number of subcarriers in a data channel.

3. The conventional interference management method

In this section, we introduce two conventional interference management methods. One is called non-erasure decoding (NED) and the other is called ED [3]. Since we assume that each UE is equipped with a log-likelihood ratio (LLR) -based iterative decoder, each UE needs to estimate the noise variance and the channel gain at each received symbol in order to calculate the LLR value.

A. LLR Calculation

The LLR value of the $k^{\underline{th}}$ bit in the $l^{\underline{th}}$ subcarrier of the subchannel allocated to the UE of interest, ***LLR(l,k)***, can be calculated as

$$LLR(l,k) = -\frac{|r_l - \widehat{r}_l(c_k = 0)|^2}{2\sigma_l^2} + \frac{|r_l - \widehat{r}_l(c_k = 1)|^2}{2\sigma_l^2}, \quad (2)$$

where σ_l^2 is the noise variance at the $l^{\underline{th}}$ subcarrier of the subchannel allocated to the UE of interest and $\widehat{r}_l(c_k = b)$ is the candidate symbol closest to the received symbol r_l among all vector symbols satisfying $c_k = b$.

B. NED and ED

If all channel gains and transmit power profiles for adjacent cells are known, the exact noise variance can be calculated as

$$\sigma_l^2 = \Sigma_{j=0,j\neq i}^{N_{cells}-1} |\ h_{j,l}|^2 \alpha_{j,l} P_{j,l} + \sigma_n^2. \quad (3)$$

In cases that we do not have any information about other cells, the NED and ED schemes can be used.

- The NED scheme [3] :

The noise variance can be approximated as

$$\sigma_l^2 \cong \sigma^2 = L^{-1} \Sigma_{l=0}^{L-1} (|r_l|^2 - P_{i,l} \widetilde{\alpha}_{i,l} |\widetilde{h}_{i,l}|^2), \quad (4)$$

where $\widetilde{h}_{i,l}$ and $\widetilde{\alpha}_{i,l}$ denote the estimates of $h_{i,l}$ and $\alpha_{i,l}$ using pilot symbols, respectively. Then, a suboptimal decoding is performed using (4) for LLR computations of all symbols in a subchannel.

- The ED scheme [3]:

In non-uniformly interfered cases, the received power of high interfered symbols tends to be abnormally large. Such symbols can be erased and the noise variance is then recalculated using only unerased symbols, which leads to more reliable decoding [3]. In other words, we erase the $l^{\underline{th}}$ symbol of the subchannel allocated to the UE of interest, r_l, if $|r_l|^2 \geq T_{i,l}$, where $T_{i,l} = |\widetilde{h}_{i,l}|^2 + T_2 \sigma^2$ (T_2 is a constant value) is the threshold for the erasure. Otherwise, the received symbol remains unchanged. The noise variance is then re-estimated with the set of non-erased symbols, *U*, as

$$\sigma_l^2 \cong \bar{\sigma}^2 = |U|^{-1} \Sigma_{l \in U} (|r_l|^2 - P_{i,l} \widetilde{\alpha}_{i,l} |\widetilde{h}_{i,l}|^2), \quad (5)$$

where $|U|$ is the cardinality of *U*.

4. THE PROPOSED INTER-CELL INTERFERENCE MANAGEMENT SCHEME

The conventional methods shown in Section III do not need any information about other cells. However, it was shown that their performance is not satisfactory when the number of subchannels allocated to cell-edge users is not small [3].

What if we were able to snatch some information about the interfering cells and use them in estimating the noise variance more accurately? Using the information, we might improve the performance of cell-edge users. In this section, we introduce a new ICI management algorithm which applies the NED, the ED, and a proposed interference estimation method adaptively.

A. The Cell-specific Information Signal

A UE receives a slot, which consists of the cell-specific information signal, pilot channel, and data channels from the serving BS. This is a basic information that a UE can obtain for the cell which it belongs to. In addition, a UE at cell-edge may receive adjacent cells' cell-specific information signals, which contain the power allocation information (power profile) of the adjacent cells. If the UE is able to decode two or more cell-specific information signals coming from other BSs, the UE will get better estimates on the ICI. In power-limited cases, we do not need to care much about getting the cell-specific information signals since interference would be so small that it can be ignored. In interference-limited cases, however, the interference cannot be ignored. Therefore, in order to receive this signal more reliably at cell edge, it is desirable to apply a frequency reuse scheme for the cell-specific information field.

TABLE 1. The Proposed ICI Management Algorithm

STEPS	CONTENTS
[Step 1]	Search cells and decide which cells to be considered. If it is successful, go to [Step 2] If not, go to [Step 4].
[Step 2]	Decode the cell-specific information signal. If it is successful, go to [Step 3]. If not, go to [Step 4].
[Step 3]	Compute the noise variance with the proposed inter-cell interference estimation method.
[Step 4]	Compute the noise variance with the ED or NED schemes.
[Step 5]	Compute the LLR values and decode the data channel.

B. The Proposed ICI Power Estimation Method

In addition to the cell-specific information signal, the average channel gain of an adjacent cell *j* ($\widetilde{\alpha}_{j,l}$) can be estimated if the adjacent cell is found during the adjacent cell search process. With the obtained other cell's power profile information and the estimated average channel gain, the cell-edge UEs can estimate the ICI power from the interfering cells. We can calculate the noise variance on the $l^{\underline{th}}$ subcarrier of the subchannel allocated to the UE of interest as

$$\sigma_l^2 = \Sigma_{j=0,j\neq i}^{N_{cells}-1} \widetilde{\alpha}_{j,l} P_{j,l} + \sigma_n^2. \quad (6)$$

In the case where the UE is not able to decode any cell-specific information of adjacent cells, the ED or the NED scheme can be used instead.

C. The Proposed ICI Management Algorithm

The proposed algorithm starts off with searching the adjacent cells. The UE finds out adjacent cells and decide which cells to choose among them in order to minimize the complexity of the noise variance estimation. If the UE cannot detect any adjacent cells, either the ED or the NED scheme is used. Once the cell-searching step is successfully performed, the cell-specific information signal of the selected cells is decoded. If the cell-specific information can be obtained through the decoding step, the noise variance is estimated by using (6). If the cell-specific is not obtained, either the ED or the NED scheme is used. The proposed interference management algorithm can be summarized in Table 1.

Remark: In [Step 4], choosing the decoding method between the NED and the ED scheme depends on D. When $D < D_{th}$, we use the ED scheme. Otherwise, we use the NED scheme. For simulations, we use $D_{th} = 2$ in this paper.

TABLE 2. Simulation Parameters

Parameter	Values
Number of Cells	3
Bandwidth	10MHz
Channel model	ITU-R, Ped. A
Path loss (α)	4
Modulation	QPSK
LDPC code rate (*K*/*N*)	1/6, 1/3
FFT size	1024
Number of Guard Subcarriers, Left	87
Number of Guard Subcarriers, Right	86
Number of Used Subcarriers (N_{used})	851
Number of data Subcarriers in a subchannel	768
Number of data channels in a slot	16

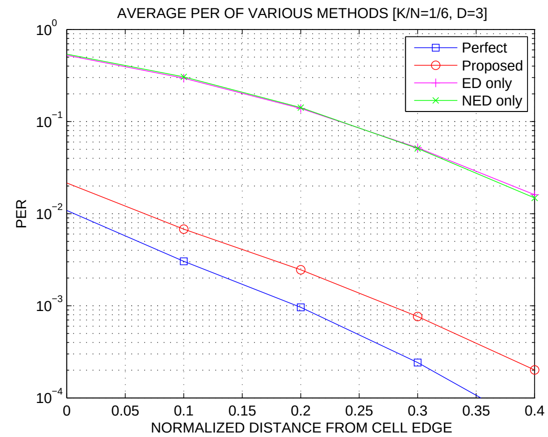

Figure 4. Average PER of various methods when *K*/*N*=1/6 and *D*=3

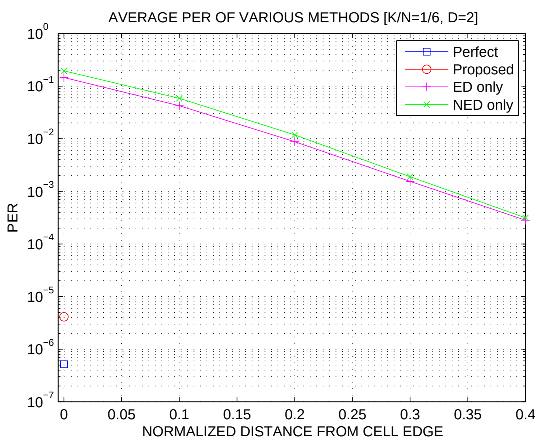

Figure 3. Average PER of various methods when *K*/*N*=1/6 and *D*=2

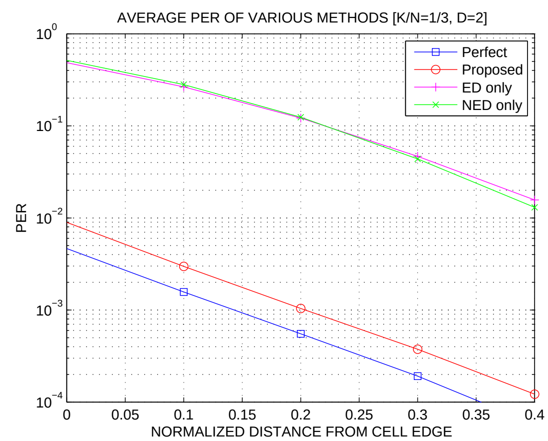

Figure 5. Average PER of various methods when *K*/*N*=1/3 and *D*=2

5. Simulation Results

A. Simulation Environment

We consider a three-cell environment as shown in Fig. 2. Table 2 shows the parameters used in the simulation. QPSK modulation and 1/6 and 1/3 binary irregular LDPC codes are used. The data channel structure is similar to that of IEEE 802.16e. The ITU-R Pedestrian A channel model is used and the pathloss exponent is set to 4. The number of data channels in a slot is 16. In the simulation, we activate all 16 data channels and D data channels out of the 16 data channels are assigned with power exceeding P_2 (and less than P_1) for every cell, which can be considered as the worst case. We also assume that for each user, a power control is performed at the BS in order to meet the target signal-to-noise ratio (SNR), not a signal-to-interference and noise ratio (SINR), at the receiver. Here, the target SNR is set to be slightly higher (with 2 dB margin) than that in a single-cell case. The packet error rate (PER) performance of the desired user is obtained by averaging over multipath fading and random interference power profiles.

B. The PER Performance

In Figs. 3-6, the average PER performance of the desired user is shown for various values of the code rate and the maximum number of channels allowed to outer-cell users. In each figure, the abscissa represents the distance from the cell edge to the desired user normalized by the cell radius $1 - \frac{r}{R}$ while the ordinate represents the PER performance averaged over multipath fadings of all users and random interference power profiles of all interfering cells. The perfect case assumes that the exact ICI power (3) is available at the receiver. Also, the performance of the ED only scheme and the NED only scheme are also shown for comparison with the proposed ICI management scheme. Fig. 3 shows the average PER performance of the four schemes when 1/6-rate LDPC code is used and the maximum number of cell-edge UEs D is set to 2. Thus, the UE of interest is mainly interfered by 4 cell-edge interferers from the two adjacent cells. If the target average PER is 10^{-2}, we can see that the average PER of the proposed ICI management scheme satisfies the target average PER even at the cell boundary, which means that the proposed scheme allows a reliable communication to the UE of interest wherever it is located. However, both the ED and the NED

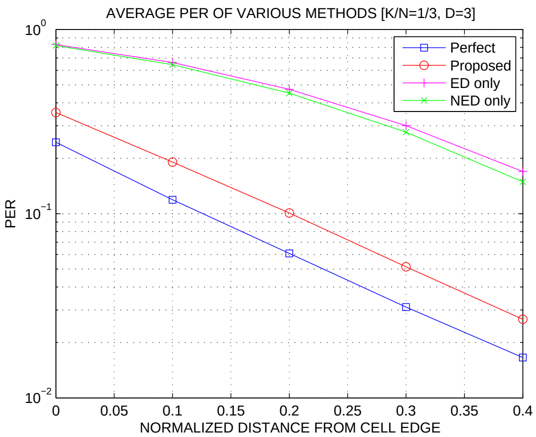

Figure 6. Average PER of various methods when K/N=1/3 and D=3

schemes cannot support the cell-edge users and only support users away from the cell edge more than 0.25R.

In Fig. 4, the number of allowable channels for cell-edge users is set to 3, which means that the number of main interferers increases to 6. However, it was shown that the average PER performance of the proposed scheme is less than the target PER except for the cell-edge users located in [0, 0.09R] away from the cell boundary. Because it is the worst-case performance in the sense that all main interferers are located at cell boundary and that the average PER is slightly higher than the target PER even at the cell boundary, we can say that the proposed scheme can support cell-edge users in this case. However, the ED and the NED schemes cannot meet the target PER for almost all locations in the outer-cell region.

In Figs. 5 and 6, we increase the data rate for cell-edge users by using a 1/3-rate code while other conditions are the same to those used in Figs. 3 and 4. In both cases, the average PER performance is degraded compared to that using 1/6-rate code. Fig. 5 shows that the proposed scheme can support the increased data rate for all cell-edge users when D=2. However, Fig. 6 shows that we cannot support the increased data rate when D=3 even in the perfect case.

6. Conclusion

In this paper, we proposed an adaptive ICI management scheme for downlink FH-OFDMA systems. By acquiring adjacent cells' information without any cooperation between cells, the proposed ICI management scheme allows us to provide much more reliable communication to cell-edge users compared to the conventional schemes. We compared the average PER performance of the proposed scheme with those of the conventional ED and NED schemes in a three-cell environment where a power control is performed for each UE based only on SNR, which is quite a practical assumption because it does not need ICI power information for power control. From the simulation results, it is shown that the proposed scheme can increase the maximum number of data channels allowed for cell-edge users up to 3 when using 1/6-rate code and up to 2 when using 1/3-rate code if the target average PER is set to 10^{-2}. By using the conventional schemes, it was shown that only one channel is allowed for cell-edge users when using 1/6-rate code and that 1/3-rate code cannot be used in the outer region, which severely limits the performance in the outer region. Since the proposed ICI management scheme does not need any inter-cell cooperation or power control (or rate control, similarly) based on the knowledge of ICI power, it can easily applied to a practical FH-OFDMA cellular system for improved performance, especially for cell-boundary users.

Acknowledgment

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