Downlink Transmit Power Allocation in Soft Fractional Frequency Reuse Systems

Donghee Kim, Jae Young Ahn, and Hojoon Kim

Downlink transmit power allocation schemes are proposed for soft fractional frequency reuse (FFR) in loose and tightly coordinated systems. The transmit powers are allocated so that the loss of spectral efficiency from the soft FFR is minimized, and the required cell edge user throughput is guaranteed. The effect of the soft FFR on spectral efficiency is evaluated depending on the power allocation schemes and the number of subbands. Results show that the loss of spectral efficiency from the soft FFR can be reduced by configuring an appropriate number of subbands in the loosely coordinated systems. In tightly coordinated systems, results show that the loss of spectral efficiency can be minimized regardless of the number of subbands due to its fast coordination.

Keywords: Spectral efficiency, fractional frequency reuse, intercell interference, power allocation, cellular systems.

I. Introduction

With the evolution of cellular systems, more focus is moving toward technologies that can mitigate or control intercell interference [1], [2]. Fractional frequency reuse (FFR) is one of the technologies effective in the enhancement of cell edge user throughput [3]-[6]. FFR systems use different frequency reuse factors (FRFs) for different frequency resources such as subbands (or time resources such as subframes) while traditional frequency reuse systems that apply FRF for all the subbands. For example, an FFR system can assign FRF of one to a group of subbands and FRF of three to the other group of subbands [3], [4]. The system can enhance the cell edge throughput by scheduling cell edge users to subbands with an FRF of three where a cell edge user experiences less intercell interference.

The FFR can be classified according to power allocation scheme into two different types: hard FFR and soft FFR [3]. As mentioned, the hard FFR assigns no transmit power on some subbands using an FRF of three to reduce intercell interference. In the hard FFR, intercell interference is managed by coordinating subbands permutation of different FRFs between neighboring cells insuring the subbands of full transmit power avoid collision between neighboring cells [3], [4]. For the coordination, graph coloring using interference graph was also introduced in [5], and dynamic channel allocation with opportunistic scheduling was proposed in [6].

A more flexible version of FFR is a soft FFR [7]-[12]. The soft FFR assigns subbands a reduced amount of transmit power, rather than no transmit power, to reduce intercell interference. The transmit power needs to be reduced enough to provide required throughput to cell edge users of neighboring cells. Also, the subbands of reduced transmit

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power are used for the inner cell users. Compared with universal frequency reuse (UFR) using FRF of one for all the subbands where the same average transmit power is assigned to all subbands, the soft FFR sets different transmit powers on different subbands, and neighboring cells are coordinated to avoid collision of high transmit power allocation on the same subband.

The capacity of the soft FFR was evaluated in [7] assuming the offset in the transmit powers of different subbands. The performance was compared with the hard FFR in [8], and it was shown that the soft FFR performs better than the hard FFR in throughput due to its flexibility in transmit power assignment. Performance considering uplink power control was shown in [9]. Self-organization of the transmit power in the uncoordinated systems was shown in [11], [12] where some transient time is required to converge on the equilibrium state of power allocation.

In this paper, downlink power allocation schemes are proposed for the soft FFR rather than simply setting an offset in the transmit power between subbands. The transmit powers are allocated so that the loss of spectral efficiency from the soft FFR is minimized, and the required cell edge user throughput is guaranteed. Different power allocation schemes are proposed depending on the tightness of coordination between neighboring cells, such as the loosely coordinated systems and the tightly coordinated systems. For the evaluation, the spectral efficiency represented by the average user throughput is obtained for different schemes. The FFR decreases frequency reuse, and thus it introduces less efficient frequency utilization than UFR that utilize spectral resource maximally. The loss of spectral efficiency in the FFR is evaluated depending on the subband power allocation schemes and system parameters, such as the number of subbands.

A system model is described in section II. In section III, subband power allocation and average user throughput is shown for UFR, loosely coordinated FFR, and tightly coordinated FFR. Evaluation results and discussions are shown in section IV, and a conclusion is given in section V.

II. System Model

The N_c cells facing each other in a hexagonal area are coordinated for FFR. The case in which N_c is three is shown in Fig. 1. The cells facing each other are defined as dominant interfering cells (DICs). In Fig. 1, each cell has two DICs. Other than these DICs, there can be many other interfering cells that are defined as non-dominant interfering cells (NDICs). The center of the hexagonal area is defined by the most interfering point (MIP). The distance from the cell site to the MIP is r_b.

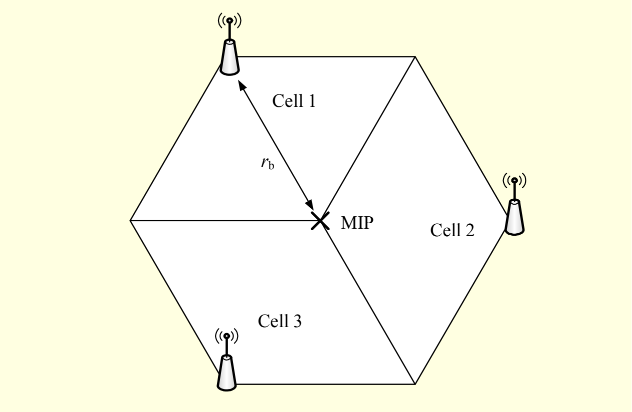

Fig. 1. Configuration of dominant interfering cells.

In each cell, N_{user} users are uniformly distributed. The bandwidths of the cells are the same and are equally divided by N_{sub} subbands. Transmit power matrix $\mathbf{P}_t$ is defined as

$$\mathbf{P}_t = \begin{bmatrix} P_{1,1} & P_{2,1} & \cdots & P_{N_c,1} \\ P_{1,2} & P_{2,2} & \cdots & P_{N_c,2} \\ \vdots & \vdots & & \vdots \\ P_{1,N_{\text{sub}}} & P_{2,N_{\text{sub}}} & \cdots & P_{N_c,N_{\text{sub}}} \end{bmatrix}, \tag{1}$$

where $P_{n,m}$ is the transmit power of the m-th subband in the n-th cell. For FFR, if the N_c cells are connected by a high-speed backbone, the transmit power matrix of cells can be shared dynamically, which means the coordination occurred in every scheduling period. If the connection between cells is not that fast, cells can share the transmit power matrix in a quasi-static manner or the management server may coordinate the transmit power of the cells on a long term basis [5].

III. Subband Power Allocation

1. Universal Frequency Reuse

In UFR, the total transmit power of a cell, P_T, is divided into N_{sub} subbands equally so that $P_{n,m}=P_T/N_{\text{sub}}$. The transmit power matrix of universal frequency reuse, $\mathbf{P}_t|_{\text{UFR}}$, is

$$\mathbf{P}_t\big|_{\text{UFR}} = \begin{bmatrix} P_{\text{mid}} & P_{\text{mid}} & P_{\text{mid}} \\ P_{\text{mid}} & P_{\text{mid}} & P_{\text{mid}} \\ \vdots & \vdots & \vdots \\ P_{\text{mid}} & P_{\text{mid}} & P_{\text{mid}} \end{bmatrix}, \tag{2}$$

where P_{mid} is P_T/N_{sub}. All the subbands use the same transmit power. The spectral efficiency of a cell edge user located at MIP, $T_{\text{edge}}|_{\text{UFR}}$, can be calculated as follows based on Shannon's AWGN channel capacity expression. In this paper, the spectral efficiency is used interchangeably with the average user throughput in the terminology used. Note that

$$T_{\mathrm{edge}}\Big|_{\mathrm{UFR}} = E\left[\log_2\left(1+\frac{P_{\mathrm{mid}}r_b^{-\delta}10^{x_n/10}}{P_{\mathrm{mid}}r_b^{-\delta}\sum\limits_{i\in\mathrm{DIC}}10^{x_i/10}+I_{\mathrm{NDIC}}+\sigma^2}\right)\right], \tag{3}$$

where δ is a path loss exponent. The symbol x_i is used for shadowing from an i-th cell to a user which is a Gaussian random variable with zero mean and standard deviation of σ_{shadow}. This x_i has a correlation of 0.5 between cells [13]. The first term of the denominator is the interference from DICs, and I_{NDIC} is the interference from the NDICs. Also, σ^2 is the thermal noise power. The numerator is the received signal power at the cell edge user. Fast fading introduced from multipath propagation is not assumed in this paper. Here, we consider practical systems which usually collect information on interference in a long term basis. Users needs some time to accumulate enough samples for an interference measure, and the frequency of a report on the interference status from users is limited due to uplink feedback overheads. Using gap analysis, (3) can be also expressed as follows taking out the effect of shadowing as gain $G_{\mathrm{s,UFR}}$ [13]:

$$T_{\mathrm{edge}}\Big|_{\mathrm{UFR}} = G_{\mathrm{s,UFR}}\times\log_2\left(1+\frac{P_{\mathrm{mid}}r_b^{-\delta}}{2P_{\mathrm{mid}}r_b^{-\delta}+I_{\mathrm{NDIC}}+\sigma^2}\right). \tag{4}$$

2. Soft Fractional Frequency Reuse

In this section, the transmit power allocation schemes for the soft FFR in the loosely and tightly coordinated cells is discussed. To enhance cell edge user throughput by K times compared with that of UFR, different transmit powers are used in each subband.

A. Loosely Coordinated Cells

Transmit powers for N_{high} subbands among N_{sub} subbands are set as P_{high} ($>P_{\mathrm{mid}}$) in each cell. When a cell sets the transmit power for a subband as P_{high}, the transmit powers of DICs for that subband are set as P_{low} to reduce interference. The number of subbands allocated as P_{low}, N_{low}, is equal to $2N_{\mathrm{high}}$ because there are two DICs, and therefore N_{high} should not exceed $N_{\mathrm{sub}}/3$. To keep the total transmit power as P_{T} ($=N_{\mathrm{sub}}\times P_{\mathrm{mid}}$), P_{high} and P_{low} have a relation with P_{mid}, such as $3P_{\mathrm{mid}} = P_{\mathrm{high}} + 2P_{\mathrm{low}}$. Thus, P_{low} can be calculated as

$$P_{\mathrm{low}} = \frac{3P_{\mathrm{mid}}-P_{\mathrm{high}}}{2}. \tag{5}$$

When N_{high} is 1, the transmit power matrix of fractional frequency reuse in loosely coordinated cells, $\mathbf{P}_{\mathrm{t}}\,|_{\mathrm{LC\_FFR}}$, is

$$\mathbf{P}_{\mathrm{t}}\Big|_{\mathrm{LC\_FFR}} = \begin{bmatrix} P_{\mathrm{high}} & P_{\mathrm{low}} & P_{\mathrm{low}} \\ P_{\mathrm{mid}} & P_{\mathrm{mid}} & P_{\mathrm{mid}} \\ P_{\mathrm{low}} & P_{\mathrm{high}} & P_{\mathrm{low}} \\ P_{\mathrm{mid}} & P_{\mathrm{mid}} & P_{\mathrm{mid}} \\ P_{\mathrm{low}} & P_{\mathrm{low}} & P_{\mathrm{high}} \\ \vdots & \vdots & \vdots \\ P_{\mathrm{mid}} & P_{\mathrm{mid}} & P_{\mathrm{mid}} \end{bmatrix}. \tag{6}$$

In each column, there is one P_{high} subband and two P_{low} subbands. The position of these three subbands is the management server’s decision coordinating neighboring these three cells. Other than these three subbands, the transmit powers of all the subbands are allocated as P_{mid}. Because cells 1, 2, and 3 are DICs with each other, when $P_{1,1}$ is set as P_{high}, $P_{2,1}$ and $\mathrm{P}_{3,1}$ are set as P_{low}.

If a cell edge user located at the MIP is served in the subband of P_{high}, the throughput of cell edge user $T_{\mathrm{edge}}|_{\mathrm{FFR}}$ can be calculated as

$$T_{\mathrm{edge}}\Big|_{\mathrm{FFR}} = G_{\mathrm{s,FFR}}\,\log_2\left(1+\frac{P_{\mathrm{high}}r_b^{-\delta}}{2P_{\mathrm{low}}r_b^{-\delta}+I_{\mathrm{NDIC}}+\sigma^2}\right), \tag{7}$$

where $G_{\mathrm{s,FFR}}$ is the shadowing gain. To enhance the cell edge user throughput by K times, for example, $T_{\mathrm{edge}}|_{\mathrm{FFR}} = KT_{\mathrm{edge}}|_{\mathrm{UFR}}$, P_{high} can be determined using (4), (5), and (7) as follows:

$$P_{\mathrm{high}} = \frac{(A^{K'}-1)(3P_{\mathrm{mid}}r_b^{-\delta}+I_{\mathrm{NDIC}}+\sigma^2)}{A^{K'}r_b^{-\delta}}, \tag{8}$$

where

$$A = 1+\frac{P_{\mathrm{mid}}r_b^{-\delta}}{2P_{\mathrm{mid}}r_b^{-\delta}+I_{\mathrm{NDIC}}+\sigma^2} \text{ and } K' = K\times\frac{G_{\mathrm{s,UFR}}}{G_{\mathrm{s,FFR}}}.$$

The average cell throughput of a subband is the sum of each user throughput of that subband. The average cell throughput of the whole bandwidth is the sum of the average cell throughputs of all subbands. The average user throughput is obtained by normalizing the average cell throughput by N_{user} and N_{sub}. The average user throughput per subband, $T_{\mathrm{avg}}|_{\mathrm{LC\_FFR}}$, can be calculated as

$$T_{\mathrm{avg}}\Big|_{\mathrm{LC\_FFR}} = \frac{1}{N_{\mathrm{user}}}\frac{1}{N_{\mathrm{sub}}}\times E\left[\sum_i\sum_m\log_2\left(1+\frac{P_{1,m}r_{1,i}^{-\delta}10^{x_1/10}}{P_{2,m}r_{2,i}^{-\delta}10^{x_2/10}+P_{3,m}r_{3,i}^{-\delta}10^{x_3/10}+I_{\mathrm{NDIC}}+\sigma^2}\right)\right], \tag{9}$$

where $P_{n,m}$ is the transmit power of the m-th subband in the n-th cell, and $r_{n,i}$ is the distance between the i-th user and n-th cell.

B. Tightly Coordinated Cells

In tightly coordinated cells, subband power allocation can be changed packet by packet. The system can use the following transmit power matrix $\mathbf{P}_{\mathrm{t}}|_{\mathrm{TC\_FFR}}$:

$$\mathbf{P}_{\mathrm{t}}\Big|_{\mathrm{TC\_FFR}}=\begin{cases}\mathbf{P}_{\mathrm{t}}\Big|_{\mathrm{UFR}} & \text{if } T_i\Big|_{\mathrm{UFR}}\geq T_{\mathrm{edge,required}},\\ \mathbf{P}_{\mathrm{t}}\Big|_{\mathrm{LC\_FFR}} & \text{else.}\end{cases} \tag{10}$$

In each scheduling period, the scheduler in each cell selects which user to serve. If the expected throughputs of selected users meet $T_{\mathrm{edge,required}}$ with $\mathbf{P}_{\mathrm{t}}|_{\mathrm{UFR}}$, the system uses the universal frequency reuse with $\mathbf{P}_{\mathrm{t}}|_{\mathrm{UFR}}$. If the expected throughput of any selected user does not meet $T_{\mathrm{edge,required}}$ with $\mathbf{P}_{\mathrm{t}}|_{\mathrm{UFR}}$, the system uses FFR with $\mathbf{P}_{\mathrm{t}}|_{\mathrm{LC\_FFR}}$.

Because the subband power allocation depends on the user scheduled, the average cell throughput is averaged over all the users. The average user throughput per subband $T_{\mathrm{avg}}|_{\mathrm{TC\_FFR}}$ can be calculated as

$$T_{\mathrm{avg}}\Big|_{\mathrm{TC\_FFR}}=\frac{1}{N_{\mathrm{user}}^{2}}\frac{1}{N_{\mathrm{sub}}}\times E\left[\sum_{k}\sum_{i}\sum_{m}\log_2\left(1+\frac{P_{1,m}^{k}r_{1,i}^{-\delta}10^{x_1/10}}{P_{2,m}^{k}r_{2,i}^{-\delta}10^{x_2/10}+P_{3,m}^{k}r_{3,i}^{-\delta}10^{x_3/10}+I_{\mathrm{NDIC}}+\sigma^2}\right)\right], \tag{11}$$

where $P^{k}_{n,m}$ is the allocated transmit power for the *k*-th user in the *m*-th subband of the *n*-th cell.

IV. Results and Discussions

P_{T} and the total bandwidth are normalized as 1. N_{user} and r_b are set as 20 and 100 m, respectively. δ is assumed to be 4 and 8.9 dB is used for σ_{shadow}. Through the gap analysis of shadowing, $G_{\mathrm{s,UFR}}$ and $G_{\mathrm{s,FFR}}$ is obtained [13]. $G_{\mathrm{s,UFR}}$ is 1.41, and $G_{\mathrm{s,FFR}}$ is between 1.41 and 1.43, according to P_{high}. Here, $G_{\mathrm{s,FFR}}$ is assumed to be 1.41 in all the range for our convenience. $I_{\mathrm{NDIC}}+\sigma^2$ is set as $2P_{\mathrm{mid}}r_b^{-\delta}$. This means that the uncontrollable interference and noise are assumed to be the same with the interference from two DICs for a cell edge user located at the MIP.

In Fig. 2, P_{high} according to cell edge throughput enhancement is shown. Cell edge throughput enhancement is defined by K shown in (8). In the figure, a 400% cell edge throughput enhancement means that the cell edge throughput of FFR are enhanced by four times compared to that of UFR, for example, K is 4. Here, N_{sub} is assumed to be 3. Thus, P_{high} is 1/3 at 100% of cell edge throughput enhancement, which is the same with P_{mid}. According to (8), P_{high} is increased as K is increased. As K goes to 4, P_{high} occupies almost all the power available in a cell. If $I_{\mathrm{NDIC}}+\sigma^2$ is assumed to be smaller than $2P_{\mathrm{mid}}r_b^{-\delta}$, K can be increased so as to be larger than 4.

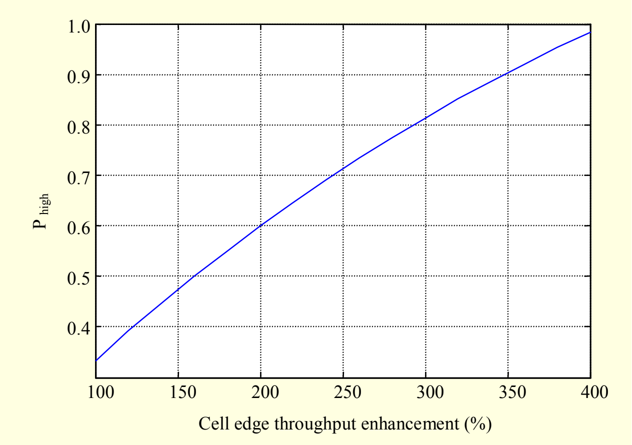

Fig. 2. P_{high} according to cell edge throughput enhancement.

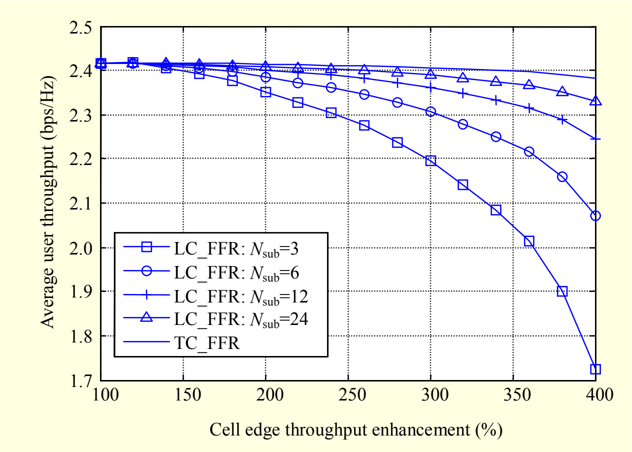

Fig. 3. Average user throughput according to cell edge throughput enhancement.

In Fig. 3, average user throughput according to cell edge throughput enhancement is shown for $N_{\mathrm{high}}=1$. As K is increased, the average user throughput is decreased. In LC_FFR, the loss of average user throughput is decreased as N_{sub}, the total number of subbands, is increased. This occurs because a greater portion of bandwidth is used as UFR as N_{sub} is increased, while the number of subbands used for FFR is fixed at 3. From these results we can see that in LC_FFR, the portion of N_{high} and N_{low} should be limited according to the portion of cell edge users. In TC_FFR, we can see that the loss of spectral efficiency can be minimized regardless of the number of subbands due to its fast coordination. The loss is minimized by virtue of using FFR only when it serves a cell edge user. In TC_FFR, the system can adaptively coordinate the transmit power matrix of neighboring cells according to the set of users scheduled.

V. Conclusion

Downlink power allocation schemes are proposed for soft

FFR in loose and tightly coordinated systems. The effect of soft FFR on spectral efficiency is evaluated depending on the subband power allocation schemes and the number of subbands.

In LC_FFR, subband transmit powers are allocated so that the cell edge user meets the required throughput. The loss in average cell throughput can be reduced by configuring appropriate number of subbands. The N_{high} and N_{low} should be limited according to the portion of cell edge users to minimize the loss of spectral efficiency. In TC_FFR, we can see that the loss of spectral efficiency can be minimized regardless of the number of subbands due to its fast coordination.

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