Performance of Soft Reservation-based Soft Frequency Reuse Scheme for Cellular OFDMA Systems

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***Abstract*—The conventional soft frequency reuse (SFR) scheme has been considered as a useful means of inter-cell interference coordination (ICIC) in the downlink of cellular OFDMA systems. It is based on hard reservation, which partitions the resource regions into two orthogonal portions, one solely dedicated to users in the cell center and the other solely dedicated to those in the cell edge. In this paper, we consider the variants of SFR scheme, which are based on a notion of soft reservation. As they allow for sharing a whole resource region among all or some users, the wider resource region leads to the multi-user diversity gain, whiles still maintaining a feature of interference mitigation by power control and dynamic interference avoidance by opportunistic scheduling in each cell. We demonstrate that a soft reservation-based SFR scheme can be the best means of trading off the average system throughput and edge-user throughput.**

Keywords – inter-cell interference coordination; soft fractional reuse; soft reservation; multi-user diversity; OFDMA

I. INTRODUCTION

Link adaptation has been a common means of dealing with co-channel interference (CCI) under time-varying and location-dependent situations in cellular OFDMA systems. However, it cannot be a means of improving the spectrum efficiency of users at the cell edge as it cannot reduce the CCI itself. Thus, various types of inter-cell interference coordination (ICIC) schemes are considered for combating the CCI problem in the cellular OFDMA network [1] . In general, ICIC may involve a complex optimization procedure with exchanging inter-cell information.

Meanwhile, inter-cell frequency reuse scheme is one particular type of ICIC from the previous works, which does not require for sharing any inter-cell information. It divides the frequency band into orthogonal channels, a subset of which will be allocated to the different cells so that the inter-cell interference can be mitigated by the sufficient frequency reuse distance. In the cellular OFDMA system, for example, a fractional frequency reuse (FFR) scheme is one particle example of realizing the frequency reuse strategy, which deals with the orthogonal frequency bands. In the frequency reuse scheme, the most important design criterion is to trade-off the performance gain with interference mitigation subject to the larger reuse distance and performance degradation with the reduced amount of resource. In other words, the overall system throughput must be maximized by trading off these two aspects.

There are two different types of FFR schemes: Partial Frequency Reuse (PFR) scheme [2] and Soft Frequency Reuse (SFR) scheme [3]. Dividing a resource region into two orthogonal portions, the PFR scheme employs the different frequency reuse factors (K) for the different portion in each cell, e.g., K = 1 for the resource allocated to the cell-center users and K = 3 for the resource allocated to the cell-edge users, so that all users can be loosely protected by the sufficient reuse distance. As opposed to the PFR scheme, the SFR scheme can fully use the frequency band in each cell by mitigating the inter-cell interference with power control. This particular scheme has been introduced in the early standardization stage of 3GPP LTE system. Even if no explicit specification has been provided, the ICIC parameters in the current LTE standard can be used to support the SFR scheme.

We find that the conventional PFR/SFR scheme is based on hard reservation, which partitions the resource region into two orthogonal portions, one solely dedicated to users in the cell center and the other solely dedicated to those in the cell edge. This kind of resource allocation which restricts resource region to each user can ensure an SINR gain in average manner. As described in [4] and [5], however, it hurts a multi-user diversity gain and fairness of resource allocation, especially when the users are not uniformly distributed throughout the coverage. These problems can be handled by a soft reservation mechanism, which allows for sharing a whole resource region among all or some users. By employing soft reservation, the wider resource region leads to a more multi-user diversity gain and fairer resource allocation [4][5]. However, it is not straightforward to warrant the average SINR gain.

In this paper, we consider the variants of SFR scheme, which are based on a notion of soft reservation. Our objective is to analyze their system throughput so that their performance can be characterized under the varying conditions. Ultimately, we are expecting to identify the best means of trading off the average system throughput and edge-user throughput.

The remaining of this paper is organized as follows. In Section II, we describe the SFR scheme and present its system model. A notion of soft reservation is introduced in Section III, leading to the variants of the SFR schemes. The performance characteristics of those variants are investigated in Section IV and the concluding remarks are presented in Section V.

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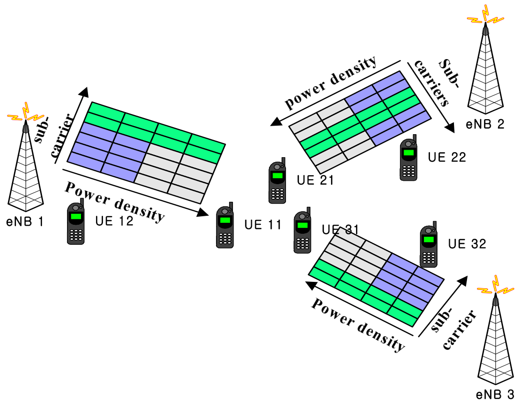


Fig. 1. Soft Frequency Reuse Scheme: Illustration [3]

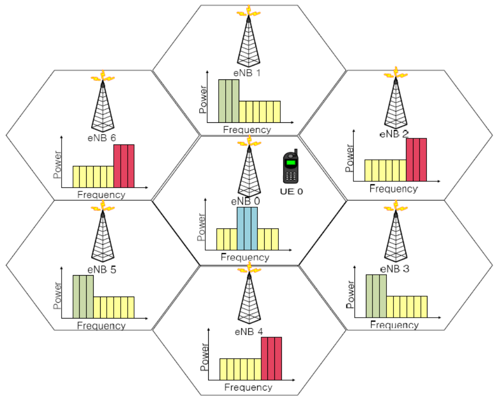


Fig 2. Power allocation pattern

II. Soft Frequency Reuse Scheme: System Model

In the soft frequency reuse (SFR) scheme, the users are classified into the different groups, depending on their location within the cell. Without loss of generality, we consider a special case of two user groups. More specifically, the users in each cell site belong to the center-user group $\mathcal{U}_C$ or edge-user group $\mathcal{U}_E$. The various design criteria can be employed to determine $\mathcal{U}_E$ and $\mathcal{U}_C$ [6]. For example, the users with their average SINR greater than the given threshold η_S are grouped into $\mathcal{U}_C$ while those with the average SINR less than η_S are grouped into $\mathcal{U}_E$ [3]. The different power levels, P_H and P_L, are employed for $\mathcal{U}_E$ and $\mathcal{U}_C$, respectively ($P_H > P_L$). As illustrated in Fig. 1, SINR of the cell-edge users will be enhanced with the higher power level and furthermore, with the partial frequency reuse, i.e., allowing no other edge users in the adjacent cells to reuse the same resource. Meanwhile, all remaining resources are allocated to the center-user group, with the lower power level, which allows for the full frequency reuse among all the cells.

In the current design, let us consider the SINR trade-off between $\mathcal{U}_E$ and $\mathcal{U}_C$ for the illustrative example in Fig. 2. Here, we assume that there is the power difference of α dB between P_H and P_L, i.e., $\alpha = P_H - P_L$ (dB). Consider a serving base station (BS) that is surrounded by 6 adjacent cells as shown by the typical hexagonal cell structure in Fig. 2. In case that all BSs are using the same power P, the corresponding signal-to-interference (SIR) for UE 0 is given as

$$SIR_{no} = \frac{P\,|h_0|^2}{P\sum_{i=1}^{6}|h_i|^2} \qquad (1)$$

where $\{h_i\}_{i=0}^{6}$ are the link gains between individual BSs and reference user, UE 0, with i =0 denoting the serving BS. Employing the power allocation pattern for a cluster of three cells as in Fig. 1, SIRs for the users in $\mathcal{U}_E$ and $\mathcal{U}_C$ are respectively given as

$$SIR_H = \frac{P_H\,|h_0|^2}{P_L\sum_{i=1}^{6}|h_i|^2} = 10^{\alpha/10}\,SIR_{no} \qquad (2)$$

$$\begin{aligned} SIR_L &= \frac{P_L\,|h_0|^2}{P_L\sum_{i=1}^{3}|h_{2\times i-1}|^2 + P_H\sum_{i=1}^{3}|h_{2\times i}|^2} \\ &= \frac{P_H\,|h_0|^2}{P_H\sum_{i=1}^{6}|h_i|^2 + (10^{\alpha/10}-1)\,P_H\sum_{i=1}^{3}|h_{2\times i}|^2} \qquad (3) \\ &\le SIR_{no} \end{aligned}$$

where $SIR_{no} = |h_0|^2 / \sum_{i=1}^{6}|h_i|^2$. The above results shows that the users in $\mathcal{U}_E$ can achieve with the SIR gain of α dB, while those in $\mathcal{U}_C$ suffer from the SIR loss in a range of $[0, \alpha]$ dB, depending their relative positions from the base stations.

III. Variants of SFR Schemes: Hard Reservation vs. Soft Reservation

In this section, we consider the variants of SFR schemes, which differ by how the resources are shared between the users in $\mathcal{U}_E$ and $\mathcal{U}_C$, for performance comparison between hard and soft reservation. An obvious reference scheme is the one that does not employ the FFR scheme while allocating the power level of P_H to all users (referred to as "Normal"). The conventional SFR scheme is characterized by hard reservation, which means that the resources are completely partitioned into two regions, one for $\mathcal{U}_E$ and the other for $\mathcal{U}_C$. Depending on whether the partitioned regions can be changed by adapting their boundary to the user distribution, it can be either dynamic or static. In the current comparative studies, we consider the static case in which the partitioned regions are fixed, i.e., referred to as "Static SFR."

Meanwhile, we consider two different variants of the static SFR schemes, which allows for sharing the reserved resource of each user group whenever necessary, e.g., when one resource region is overloaded by the non-uniform user distribution. In fact, there are two different extreme cases: one case of allowing the center users to share the resources reserved for the edge users and the other case of allowing the edge users to share the resources reserved for the center users. More specifically, the center users can employ K = 1 with the power level of P_L , i.e., allowed to borrow the resource reserved for the edge users (referred to "SFR-FCR: SFR with Full Center Reuse"). In other words, the resources for the edge users are only *softly* reserved as they are shared with the center users. As the lower power level is employed by the center users, the edge users are not suffered from the additional interference caused by soft reservation in this case.

On the other hand, the edge user can employ K = 1 with the power level of P_H , i.e., allowed to use the resource reserved for the center users (referred to "SFR-FER: SFR with Full Edge Reuse"). In this case, some edge users will be suffered from the additional interference from the edge users that share the same resource reserved for the center users in some adjacent cells. In fact, SFR-FCR and SFR-FER schemes are two extreme cases for SFR scheme subject to soft reservation.

The most generalized form of soft reservation in SFR is to share all the resources among all users in the system. As a whole resource can be used by both center and edge users, it is just the same as the conventional scheme, except that two different power levels are employed, depending on their position. The advantage of the soft reservation-based SFR (SFR-SR) scheme would be to improve a multi-user diversity gain by extending the allocation region to a whole band. As mentioned earlier, however, SFR-SR cannot maintain a fixed SINR gain, as implied by (3). Fig. 3 illustrates the various types of SFR schemes in the perspective of resource sharing and power allocation.

In order to understand the characteristics of all these schemes, a notion of *collision* must be addressed from a viewpoint of inter-cell coordination. Collision can be roughly understood as an event of failing the interference coordination that is intended by scheduling and power allocation, mainly due to the excessive other cell interference incurred by the high power level for the same resource shared between the adjacent cells. In this work, we define a rather quantitative notion of collision in the course

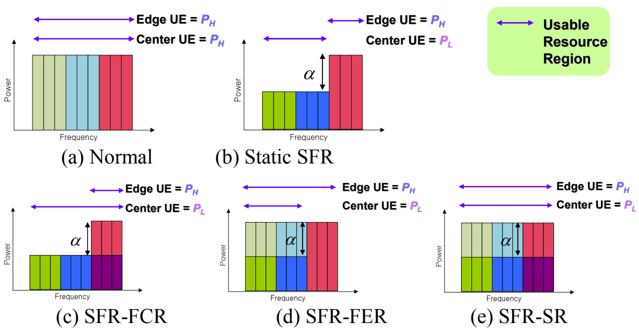


Fig. 3. Variants of SFR schemes: Comparison

of link adaptation. It is defined as an event that collision occurs when a user in $\mathcal{U}_E$ allocated to a certain resource region undergoes degradation in MCS level because its highest- interfering cell allocates P_H to the corresponding resource region.

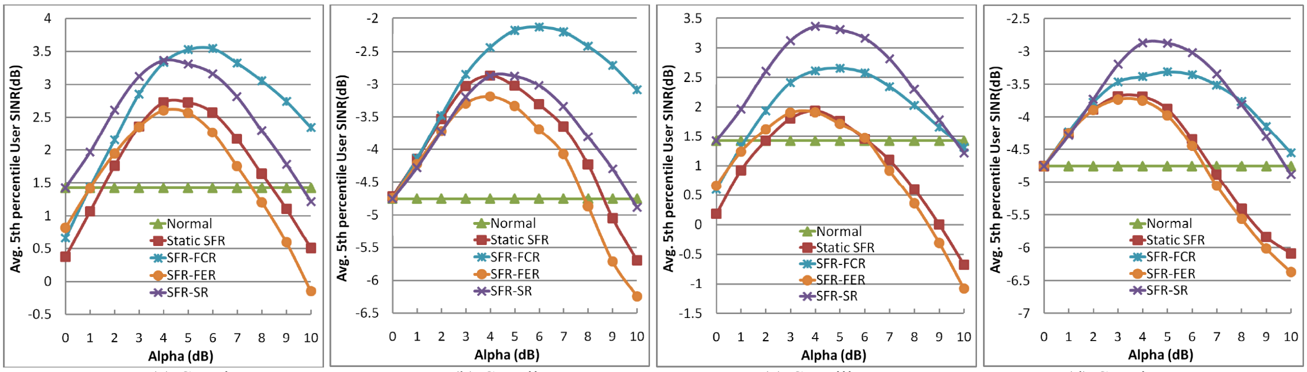
IV. PERFORMANCE ANALYSIS

Various types of the SFR schemes are evaluated with system-level simulation for 3GPP LTE system. Table 1 summarizes the simulation parameters used in the current studies, including the system parameters for LTE specification.

In order to capture the performance characteristics of individual SFR scheme, we consider four different scenarios that are varying with the fading characteristics and user-grouping criterion. We consider two different user-grouping criteria with using the different thresholds: SINR threshold and ratio threshold. More specifically, UE can be grouped into an edge user set if its SINR drops below the given SINR threshold η_S (SINR threshold-based), or if its SINR is smaller than the lowest x-th percentile SINR (load threshold-based). The SINR threshold-based grouping may suffer from the situation that may turn too many UEs into the edge- or center-user group, i.e., incurring overload to one of two partitioned regions. Such an overload problem can be solved by the load threshold-based grouping, which sets the threshold by traffic load for edge users. In the following evaluation, we employ the load threshold-based user grouping. Meanwhile, we consider both fading and non-fading channels. The performance under a non-fading

Table 1. Simulation Parameters

System Parameter		Note
The number of cells	19	3 sectors per cell
Inter-system distance	500m	-
The number of UEs per sector	10	-
Antenna configuration	SIMO	1x2 MRC
Carrier frequency	2GHz	-
Bandwidth	10MHz	FFT: 1024, 50RBs/slot
Hybrid ARQ	Chase Combining	The maximum number of retransmissions: $N_r(max) = 3$
		The number of HARQ process channels: $N_h = 8$
BS Tx power	Max: 40W (46dBm)	-
Log-normal shadowing	STD: 10dB	-
Channel model	ITU-R Pedestrian B (3km/h)	-
Noise figure	9dB	
Scheduler	Proportional fairness	T=1000
Traffic model	Full buffer	-
Link-to-system interface	Effective SNR: Mutual Information-based	IEEE802.16m EMD [7]
Link adaptation	Adaptive modulation & coding	-
CQI type	Subband CQI	The number of subbands: 9
CQI report period (T_{CQI})	2ms	Actual period for each subband: 18ms
Power ratio (α)	Variable	$\alpha = P_H - P_L$
SINR threshold for edge UE (η_S)	0dB	UE to be grouped into an edge user set if η_S <0dB
Load threshold for edge UE (x)	30%	UE with the lowest x% SINR to be grouped into the edge user set



(a) Case i (b) Case ii (c) Case iii (d) Case iv

Fig. 4. 5th percentile user SINR as varying the power ratio for different scenarios

channel would be useful for solely investigating the effect of resource allocation while eliminating the effect of opportunistic scheduling. Then, evaluations are carried for the following four different scenarios:

Case i) SINR-based grouping subject to fading
Case ii) SINR-based grouping subject to no fading
Case iii) load-based grouping subject to fading
Case iv) load-based grouping subject to no fading

A. Limitation of hard reservation: Static SFR

Fig. 4 shows the average 5th percentile user SINR while Fig. 5 shows the average 5th percentile and cell throughput at the same time, as the power difference $\alpha = P_H - P_L$ varies. As shown in Fig. 4, SINRs of all schemes increase with α up to a certain point, beyond which they decrease because the extremely high power for cell edge user would hurt the center users in the neighbor cells. In Fig 5, meanwhile, there is an obvious trade-off between 5th percentile and total average throughput as α increases up to a certain point, beyond which both 5th percentile and total average throughput decrease with α. These aspects are attributed to SINR degradation, as depicted in (3). More specifically, as the SINR of cell-center users is degraded with extremely large α, some of the center users tend to have 5th percentile SINR, which causes degradation in both 5th percentile and total throughput. The observations from Fig. 4 and Fig. 5 imply that the range of α must be carefully chosen for our comparative studies, so as to make sure that both SINR and throughput are not degraded at the same time over the given range. Note that Static SFR has neither SINR gain nor loss at $\alpha = 0$, as clearly in (2) and (3). In Fig. 4(a), however, its SINR is worse than that in the scheme that employs any ICIC ("Normal"), which is attributed to the hard reservation feature of the Static SFR. In fact, it is the feature that reduces the multi-user diversity gain in hard reservation. It is clear from Fig. 4(b), which demonstrates that there is no performance difference between Normal and Static SFR.

The same reason for aforementioned 5th percentile SINR degradation in hard reservation can explain the difference in throughput gain for each scheme between case i) and case ii) in Fig. 5. However, the difference between case i) and case iii) cannot be clearly understood by the same reason. In fact, the different grouping criterion is applied to case i) and case iii), respectively. For the SINR threshold-based grouping in case i), the number of users in each group varies with the user distribution, which may overload one resource region over the other and thus, lead to degradation in 5th percentile throughput. In case iii), meanwhile, no such degradation is expected as the number of users in the cell-edge group is pre-determined.

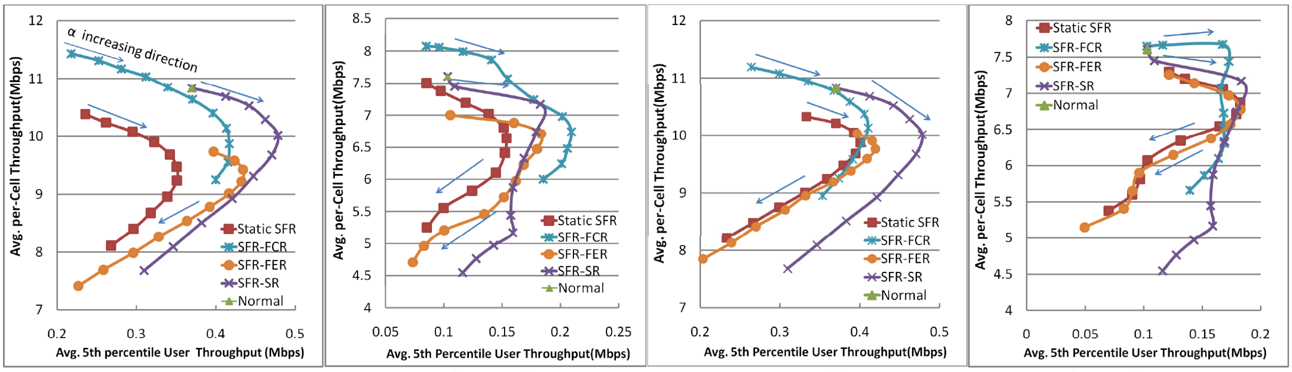
We note that Static SFR in case iv) outperforms that in case ii) or case iii) for 5th percentile throughput performance in Fig. 5. It is due to the fact that case iv) inherits both features in case ii) and case iii).

To summarize, any scheme based on hard reservation, including Static SFR, suffers from degradation in throughput performance by losing the multi-user diversity gain as well as the efficiency in resource allocation.

B. SFR-FCR vs. SFR-FER schemes

SFR-FCR and SFR-FER are SFR schemes that employ soft reservation, allowing one resource region to be shared by the other user group. Comparison between these two schemes may be useful for characterizing the performance of soft reservation.

In case i) of Fig. 4, SFR-FCR and SFR-FER have the 5th percentile SINR gain of 0.3dB and 0.5dB over that of Static SFR with $\alpha = 0$. These 5th percentile SINR gains are attributed to the multi-user diversity gain obtained by soft reservation, which is supported by observation that neither SFR-FCR nor SFR-FER show any SINR gain with $\alpha = 0$. Note that SFR-FER has the better SINR gain with $\alpha = 0$, which is due to the fact that wider resource region is used by those in the cell-edge user group, improving the multi-user diversity gain. As α increases, however, the SINR gain for SFR-FCR improves while that for SFR-FER decreases. The performance difference between SFR-FCR and SFR-FER is attributed to the situation that the low power P_L can be allocated to resource region for the cell-edge users with SFR-FCR , warranting the SINR better than (3) for the cell-center users, while the high power P_H can be allocated to resource region for the cell-center users with SFR-FER, degrading the SINR worse than (3) for the cell-center users



(a) Case i (b) Case ii (c) Case iii (d) Case iv

Fig. 5. Trade-off relation: 5th percentile vs. total throughput

in each cell.

Furthermore, SFR-FCR and SFR-FER show the opposite characteristics in the average total throughput performance. In general, SFR-FCR tends to improve the total average throughput, while SFR-FER tends to improve the 5th percentile throughput. The difference can be explained as follows. The total average throughput for SFR-FCR improves as more resource is allocated to $\mathcal{U}_C$ by soft reservation of the resource allocated to $\mathcal{U}_E$. As shown in case i) of Fig. 5, therefore, it outperforms the Normal scheme in the total average throughput, while reducing the 5th percentile throughput. By the similar reason, meanwhile, the average throughput for $\mathcal{U}_E$ improves with SFR-FER, which subsequently improves the 5th percentile throughput as the low throughput users tend to belong to $\mathcal{U}_E$. The total average throughput of SFR-FER is much worse than Normal and Static SFR, as the resource allocated to $\mathcal{U}_C$ is reduced.

In conclusion, we find that soft reservation only for one user group improves the performance of the user group subject to hard reservation. Furthermore, soft reservation of the resource for the lower SINR user group is more effective for throughput trade-off.

C. Performance of soft reservation: SFR-SR

In Fig. 4 and Fig. 5, the SFR-SR scheme turns out to provide the best trade-off performance. In Fig. 4(a), the difference among the largest SINRs of Static SFR, SFR-SER, and SFR-SR is 0.64dB, while this is 0.01dB in Fig. 4(b). It implies that SFR-SR has the larger multi-user diversity gain than SFR-FER and Static SFR, while maintaining almost the same level of SINR gain with power control for each user group as that with hard reservation in (2). Note that a soft reservation feature in SFR-SR cannot warrant the SINR gain in (2) only by the power control, without any means of inter-cell interference control. Nevertheless, it demonstrates a rather acceptable performance gain, which implies that performance degradation caused by collision is not significant. In fact, Fig. 6 shows the collision probability as varying α. Note that the collision probability of SFR-SR is twice as large as that of Static SFR, demonstrating their maximum difference of 15%. The SINR loss by the collision can be at most 2.4dB in all SFR schemes, which corresponds to reduction in the bandwidth efficiency by 1/2 or less in the low SINR region. Therefore, the collision incurs reduction in bandwidth efficiency with the probability of 0.15 or less, which is also true for the cell-edge user group.

In general, downlink interference is usually dominated by a small number of base stations only [10]. In other words, a change in total interference is mainly governed by that in the dominant interferers. When α is small as compared to the change in the channel gain, therefore, the effect of α on total interference can be negligible. When the gain of interference channel is large enough, interference is still large for any level of power over each scheduling period. Therefore, other users with the lower gain of interference channel must be allocated to the corresponding resource. The current explanation can be supported by the results in Fig. 6, which shows that the collision probability increases with α.

Meanwhile, we note that SFR-SR is free from any imbalance in resource allocation between each user group, which is caused by hard reservation, since the required resource for each user group is dynamically determined by user scheduling. Such a desirable feature supports the fact that SFR-SR provides the best trade-off relation for average throughput as shown in case iv) of Fig. 5.

V. CONCLUSION

We have shown that a soft reservation-based SFR scheme can be a useful alternative to the variants of the hard reservation-based conventional SFR scheme. More specifically, it can be more flexible and adaptive to the varying user distribution in practice. Performance analysis with our simulation for LTE system has demonstrated that the proposed soft-reservation approach performs fairly well, even if there is no explicit coordination among the neighbor cells. In fact, a virtual coordination is realized by avoiding the inter-cell interference dynamically, yet in a rather long-term basis. Furthermore, it fully exploits a multi-user diversity over a whole frequency band, as opposed to the

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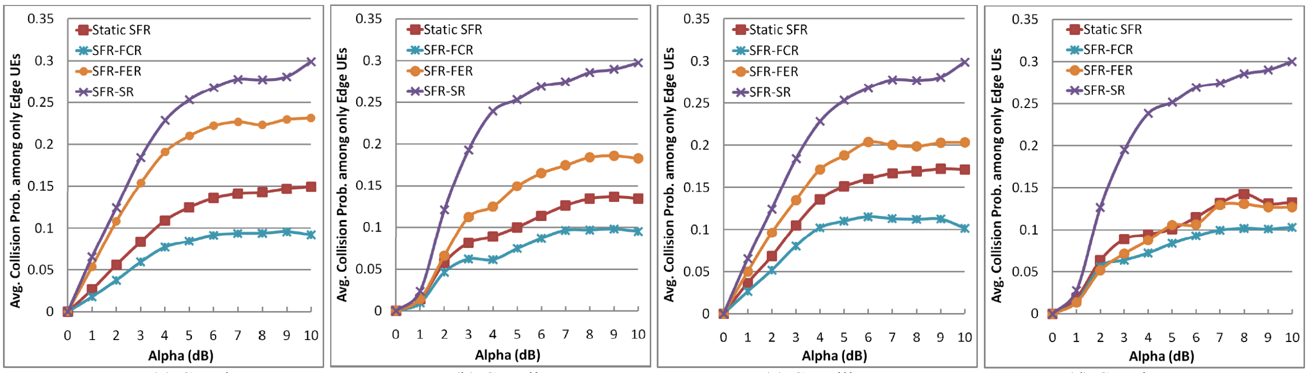

(a) Case i (b) Case ii (c) Case iii (d) Case iv

Fig. 6. Collision probability among only edge UEs

hard reservation-based SFR scheme, in which a multi-user diversity gain is limited by partitioning the resource regions in an orthogonal manner. As the overall performance depends on how frequently interference measurement is made in each cell, our future work will investigate the validity of the soft reservation-based SFR scheme upon the system dynamics and user distribution.

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