Network-Assisted Radio Resource Management for Cell-Edge Performance Enhancement

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Abstract. A number of network-level techniques have been proposed to mitigate inter-cell interference and improve throughput for cell-edge users in wide-area wireless data networks. To facilitate the coordination among base stations (BSs), we propose a new radio-resource management framework where cell-edge users and cell-interior users are separately managed by two different radio-resource managers (RRM). In the proposed framework, we address the issue of how to classify a user as cell-edge user or cell-interior user, and how much radio resource the cell-edge users may occupy. We present a solution where a user switches the RRM so as to maximize overall network throughput subject to the condition that her own throughput does not decrease upon switching. We verify our solution using analysis and simulation experiments, and demonstrate that our solution can guarantee superior cell-edge performance and achieve high network throughput.

1 Introduction

In OFDMA systems, as neighboring cells can reuse the same frequency, intercell interference is an important problem that needs to be solved. Due to intercell interference, *cell-edge users* may suffer from high error rates (and hence a reduced throughput) even when the most robust modulation and coding techniques are used. To enhance the performance of cell-edge users in OFDMA systems, frequency reuse techniques between neighboring cells, have been developed. For flexibility, dynamic fractional frequency reuse (FFR) has been widely examined [1, 2, 3], and it is known that FFR can enhance cell-edge throughput by about 15% [4] but at the expense of a reduced average cell throughput. Another technique to enhance cell-edge user performance is macro-diversity. With macro-diversity, multiple BSs can serve a user, thus making the link condition of cell-edge users more reliable and robust [5].

Both dynamic FFR and macro-diversity require coordinated RRM[1] between neighboring BSs within the network. If dynamic FFR is deployed in the system, designated neighboring BSs of a cell to which a certain cell-edge user is attached, should avoid concurrent transmission over the set of channels assigned to that user. On the other hand, if macro-diversity is used, one or more neighboring BSs should serve a certain cell-edge user at the same time; this means

[1] We use RRM to refer to both Radio Resource Management and Radio Resource Managers.

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concurrent transmissions over the same set of channels from multiple BSs to the same user is required. Network-level coordination of radio-resources through *Network-Assisted RRM* is required to handle such requirements.

In this paper, we propose a *two-level RRM* framework. We advocate the coexistence of two RRM entities, an upper-level RRM and a lower-level RRM, within the backhaul architecture that connects the BSs. We separate users attached to a BS into two groups; one group consists of users who are classified as cell-edge users and the other consists of users who are classified as cell-interior users. The RRM functions for cell-edge users are handled by the upper-level RRM, whereas those for cell-interior users are handled by the lower-level RRM.

The classification of cell-edge and cell-interior users are *not* based purely on geographic location as in conventional frequency reuse techniques. We classify users as cell-edge or cell-interior users with the goal of maximizing network throughput subject to certain conditions on the per-user throughput; for example, a user at the edge of a cell may still get classified as a cell-interior user if such classification leads to higher network throughput with no attendant loss in the user throughput or conversely if such classification increases the user throughput[2] without any noticeable loss in the network throughput. Furthermore, we also show that compared to a switching scheme which only aims to maximize the network throughput, our classification scheme results in a better cell-edge performance without a loss in network throughput. Within the proposed framework, we address three main problems: 1) initial user classification, 2) strategy to switch users from one class to another subsequently, and 3) radio-resource reservation in neighboring cells for users who are classified as cell-edge users.

2 Initial User Classification and Metrics

In this section, we introduce metrics for classifying a user as a cell-edge user to be assigned to an upper RRC, and also describe the initial classification of a new user.

2.1 Computation of User Capacities

We would like to determine the capacity a user can achieve when it belongs to the lower RRC (cell-interior user group) or an upper RRC (cell-edge user group). For simplicity, we suppose that a user is able to measure her average signal-to-interference-plus-noise ratio (SINR) as well as the average signal strengths from one dominant neighboring BS and her serving BS, respectively. In the following, we only deal with the case where a cell-edge user is served by at most two BSs, since it is easy to extend the analysis to the case where three or more BSs can serve the user.

Capacity of cell-interior users. Consider a specific lower RRC user in cell 1 and assume that it is served only by BS 1 without any cooperation by neighboring

[2] This can happen due to the multi-user diversity gain which is obtained when channel dependent scheduling is employed to serve cell interior users.

BSs. Let C_1 denote the resulting downlink capacity per unit resource and let S_1 denote the average received signal strength from BS 1 at the user of interest. Further, let the dominant interfering neighboring BS be indexed by 2 with I_2 denoting the average received signal strength from BS 2 at the user of interest. Next, let I_o be the average interference to the user (which is in cell 1) generated by neighboring BSs other than BS 2 and let N be thermal noise variance. Then, the average received SINR of the user is given by $S_1/(I_2 + I_o + N)$. C_1 is a function of this average SINR. In the case where channel independent scheduling is employed and the users are allocated rates based on their average SINRs, C_1 can be computed as

$$C_1 = \log\left(1 + \frac{S_1}{I_2 + I_o + N}\right). \tag{1}$$

Letting $\gamma_1 = S_1/(I_o + N)$ and $\gamma_2 = I_2/(I_o + N)$, we can rewrite C_1 as

$$C_1 = \log\left(1 + \frac{S_1}{\gamma_2(I_o + N) + I_o + N}\right) = \log\left(1 + \frac{\gamma_1}{\gamma_2 + 1}\right). \tag{2}$$

Note that the average SINR here is a function of the distance dependent path-loss and possibly large scale shadow fading but not of the small scale fading which changes on a much finer time scale and is assumed to be averaged out.

In case opportunistic channel dependent scheduling is employed by the base station, this capacity will increase owing to multiuser diversity. Under some assumptions on the fading process, closed-form approximations for this capacity can be derived using results in [6, 7]. Thus, when a cell-edge user tries to switch to the lower RRC, the system can approximate the expected average capacity by such expressions or more generally by using a real-time statistic that is computed from a look up table obtained by measuring user throughputs over some duration in the network.[3] Hereafter, C_1 will represent the average capacity of an interior user computed using one of these methods.

Capacity of cell-edge users. Now consider two cases where the cell-edge users are supported by, a) fractional frequency reuse, and b) macro-diversity. In each case no opportunistic scheduling is employed and the users are assigned rates based on their average SINRs.

a) Dynamic FFR – In this case, to mitigate the interference from a dominant neighboring cell at a particular cell-edge user, the two BSs (serving BS as well as the dominant interfering BS) are coordinated such that the dominant neighboring BS will not use a certain quantity of resources that is allocated to the cell-edge user. As interference from the neighboring BS is eliminated, the user can achieve a better capacity. In particular, in the above example, I_2 is removed so the user's capacity achieved by the cooperation of BSs 1 and 2 via FFR, denoted by $C_{1,2}$, is expressed as

$$C_{1,2} = \log\left(1 + \frac{S_1}{I_o + N}\right) = \log(1 + \gamma_1). \tag{3}$$

[3] We note that such a look up table is indeed required to implement the proportional fair scheduler.

b) Macro-diversity – We consider Alamouti's space-time coding [8] for supporting downlink macro-diversity. That is, the serving BS and the dominant neighboring BS transmit two signals y_1 and y_2 at the same time over the same frequency band, followed by $-y_2^*$ and y_1^*. The transmissions from the two BSs can be coherently combined using a simple receiver [8]. Then, if the user is served by an upper RRC for macro-diversity, her capacity will be given by[4]

$$C_{1,2} = \log\left(1 + \frac{S_1 + I_2}{I_o + N}\right) = \log(1 + \gamma_1 + \gamma_2). \tag{5}$$

Obviously, $C_{1,2}$ in the two cases is higher than C_1 given in (1), but some amount of resource from BS 2 needs to be additionally provisioned for this user.

2.2 Computation of Throughput

The throughput of a cell-interior user i in cell x is denoted by $T_x(i)$ and it can be expanded as $T_x(i) = \alpha(i)C_x(i)$, where $C_x(i)$ denotes the average capacity of the interior user i in cell x. $\alpha(i)$ denotes the average ratio of resource allocated to user i (e.g., the average ratio of slots or quantity of resource in the frequency and time domains). Similarly, the throughput of a cell-edge user i managed by the cooperation of BS x and BS y is denoted by $T_{x,y}(i)$ and it can be expanded as $T_{x,y}(i) = \alpha(i)C_{x,y}(i)$, where the average capacity $C_{x,y}(i)$ can be computed as in (3) or (5) depending on whether FFR or macro-diversity is employed. Note that each cell expends a fraction of its available resources to serve the cell-edge users.

The assignment of α's relies on a scheduling policy employed at the BSs. We do note that while user k is managed by the lower RRC, $\alpha(k)$ may be adjusted by the scheduling policy used or by the reclassification of other users. On the other hand, the ratio α for a cell-edge user is determined when the user is admitted into the network as a cell-edge user or when the user is switched from the lower RRC to the upper RRC. This computation will be illustrated in the sequel. However, we assume $\alpha(k)$ to be a constant value while user k is being managed by the upper RRC. This simplifying assumption is made because resource rearrangement for such users entails complex calculation involving all the combinations of pairs of neighboring BSs. To summarize, $\alpha(k)$ changes in the following cases.

- $\alpha(k)$ can decrease, if user k is managed by the lower RRC and a new user requiring the cell resource arrives.

[4] It is possible to obtain orthogonal space-time codes for three transmit antennas, which in our case correspond to the antennas at the three neighboring BSs. From [9], it can be inferred that the resulting capacity is given by

$$C_{1,2,3}(k) = \frac{3}{4} \cdot \log\left(1 + \frac{S_1 + I_2 + I_3}{I_o' + N}\right), \tag{4}$$

where I_2 and I_3 are the received signal strengths from two neighboring BSs, and I_o' is the interference from neighboring BSs other than those two BSs.

– $\alpha(k)$ can increase, if user k is managed by the lower RRC and some resource is freed due to the departure of an existing user who occupied the cell resource.
– $\alpha(k)$ can increase or decrease, if user k switches the serving RRC from a lower RRC to an upper RRC, or vice versa.
– Besides, $\alpha(k)$ is forced to change by a hand-off that occurs regardless of the classification of the user.

Let β_x be the ratio of resource in cell x allocated for cell-edge users. β_x can then be expressed as

$$\beta_x = \sum_{y \in V_x} \sum_{i \in U_{x,y}} \alpha(i), \tag{6}$$

where $U_{x,y}$ is the set of cell-edge users which are managed by the cooperation of BSs x and y, and V_x is the set of BSs which cooperate with BS x (i.e., its neighboring BSs). BS x will use the remaining resource $1-\beta_x$ for its cell-interior users. We further assume that $\beta_x \leq \beta_{\max}$ in order to avoid monopolization of the resources by the upper RRC.

2.3 Initial User Classification

A new user is admitted to the system as a cell-edge or a cell-interior user. We consider a simple scheme that guarantees a minimum throughput $T_{\min}(i)$ given by user i's QoS requirement:

$$T_x(i) \geq T_{\min}(i); T_{x,y}(j) \geq T_{\min}(j) \ \forall\ x, y, i, j. \tag{7}$$

The capacity of a new user n, $C_x(n)$, upon admission as a cell-interior user in cell x is first estimated. Similarly the capacity $C_{x,y}(n)$ of the user upon admission as a cell-edge user served by BSs x and y is also computed using (3) or (5). Then, the user can be admitted as a cell-interior user by BS x only if its minimum throughput requirement can be met, i.e., only if

$$\sum_{i \in L_x} \frac{T_{\min}(i)}{C_x(i)} + \frac{T_{\min}(n)}{C_x(n)} \leq 1 - \beta_x - \delta, \tag{8}$$

where L_x is the set of cell-interior users in cell x and δ is a margin for absorbing the change of some users' average capacities or accepting hand-off users; for our discussion, δ is considered to be a design parameter. If user n is admissible in BS x as a cell-interior user, a ratio $\alpha(n)$ is determined according to the scheduling policy adopted by BS x. Once $\alpha(n)$ is determined, the admission controller checks if there exists an $\alpha'(n)$ acceptable by BSs x and y for some $y \in V_x$ (using our upward RRC switch algorithm in Section 3) which can lead to better system and user throughputs. If such an $\alpha'(n)$ exists, the user is admitted as a cell-edge user which is served by BSs x and y; otherwise it is admitted as a cell-interior user which is served by BS x.

Notice that in (8), we have implicitly assumed that the capacity $C_x(i)$ of an existing interior user i in cell x does not change upon addition of a new user. However when channel dependent scheduling is employed this capacity may increase due to a larger multi-user diversity gain. Thus (8) is a conservative condition for admitting a new user. In general, for channel dependent scheduling, the increase in $C_x(i)$ with the addition of a new user or the decrease in $C_x(i)$ with the deletion of another interior user, is small when the number of interior users is sufficiently large (10 or more verified in simulations). Henceforth, in the case of channel dependent scheduling, we will assume a sufficiently large population of interior users in each cell and ignore this change in the average capacity of an interior user.

3 Strategy for User Reclassification

We now derive the condition for reclassifying users and switching them from upper RRC to lower RRC or vice versa. Users that do not satisfy these conditions will, by default, not be reclassified. The objective behind reclassifying users is to maximize the sum throughput over all the users in the network covered by an ASN gateway (or a set of BSs deployed for cooperation) subject to a minimum throughput guarantee for each user. In particular, the admission controller allocates each user to either a lower RRC or an upper RRC to meet the following objective:

$$\max \left[\sum_{x \in \mathcal{N}} \sum_{i \in L_x} T_x(i) + \sum_{x,y \in \mathcal{N}} \sum_{j \in U_{x,y}} T_{x,y}(j) \right] \tag{9}$$
$$T_x(i) \geq T_{\min}(i); T_{x,y}(j) \geq T_{\min}(j)\ \forall\ x, y, i, j.$$

where $\mathcal{N}$ is the set of BSs within the domain. Further, this reclassification is also subject to the condition that the switching (reclassified) user's throughput must not decrease.

We are now ready to propose our reclassification strategy in which a user is allowed to switch only if both its own throughput as well as the system throughput do not decrease and at-least one of them strictly increases.

3.1 Upward RRC Switch

We first consider an upward RRC switch algorithm, when user k tries to switch her RRC from a lower RRC to an upper RRC. Assume that the user is being served by cell 1 and the current ratio α for the user is $\alpha(k)$. Suppose user k's ratio changes to $\alpha'(k)$ after the RRC switch, when she is supposed to be managed by BSs 1 and 2. User k will accept the RRC change when her throughput becomes higher by changing the RRC, so the first condition for reclassification is

$$\alpha'(k)C_{1,2}(k) - \alpha(k)C_1(k) \geq 0. \tag{10}$$

Since $\alpha'(k)C_{1,2}(k) \geq \alpha(k)C_1(k) \geq T_{\min}(k)$, the condition in (10) will ensure that the minimum throughput requirement will also be satisfied post-switching.

Next, we consider the impact of switching on system throughput which is more involved. In particular there are three factors that must be accounted for:

- *The throughput loss in cell 2*: Notice that user k post-switching will take an additional resource $\alpha'(k)$ from BS 2 which could have been used for other users in that cell if it had not been used for dynamic FFR or macro-diversity. However, it is very hard to precisely estimate this throughput loss since it depends on the cell 2's scheduling rule. Consequently, we use a simple way to quantify this loss as $\alpha'(k) \cdot \overline{C}_2$, where $\overline{C}_2$ is the average per-user capacity of cell 2's interior users[5].
- *The throughput change in cell 1*: The throughput of the current serving cell (cell 1) can change due to switching in the following manner. First, if $\alpha'(k) < \alpha(k)$, the residual part $\alpha(k) - \alpha'(k)$ will be distributed among cell 1's interior users and together they will achieve an average throughput gain of $(\alpha(k) - \alpha'(k)) \cdot \overline{C}_1$, where $\overline{C}_1$ is the average per-user capacity of cell 1's interior users (excluding user k). Otherwise, i.e., if $\alpha'(k) > \alpha(k)$, cell 1's interior users will lose an average throughput of $(\alpha'(k) - \alpha(k)) \cdot \overline{C}_1$. In either case, the net throughput change in cell 1 is expressed by $(\alpha(k) - \alpha'(k)) \cdot \overline{C}_1$.
- *System constraints*: We must ensure that the switching operation does not violate the minimum throughput requirement of any user or the maximum limit on the resource ratio reserved for cell-edge users in any cell. Specifically, if either $\beta_1 + \alpha'(k)$ or $\beta_2 + \alpha'(k)$ is greater than $\beta_{\max}$, or the additional resource $\alpha'(k)$ taken from BS 2 or $\alpha'(k) - \alpha(k)$ taken from BS 1 (when $\alpha'(k) > \alpha(k)$) jeopardizes the minimum allocation for users in L_2 or $L_1 - \{k\}$, user k cannot be allowed to use $\alpha'(k)$ by the upper RRC.

Thus, the first two conditions dictate that a post-switching ratio $\alpha'(k)$ chosen to maximize the network-side throughput in eq. (9), should satisfy

$$\alpha'(k)[C_{1,2}(k) - \overline{C}_1 - \overline{C}_2] - \alpha(k)[C_1(k) - \overline{C}_1] \geq 0 \tag{11}$$

On the other hand, the system constraints impose that $\alpha'(k)$ should also be constrained to satisfy:

$$\begin{aligned} &\alpha'(k) \leq \min[\beta_{\max} - \beta_1, \beta_{\max} - \beta_2, \\ &1 - \beta_1 - \sum_{i \in L_1 - \{k\}} \frac{T_{\min}(i)}{C_1(i)}, 1 - \beta_2 - \sum_{i \in L_2} \frac{T_{\min}(i)}{C_2(i)}]. \end{aligned} \tag{12}$$

Thus, the optimal ratio $\alpha'(k)$ can be determined by solving the following optimization problem:

$$\begin{aligned} \max\ &\alpha'(k)[C_{1,2}(k) - \overline{C}_1 - \overline{C}_2] - \alpha(k)[C_1(k) - \overline{C}_1] \\ &\text{subject to } (10), (11) \text{ and } (12). \end{aligned} \tag{13}$$

The solution for the above objective is given by the following proposition which is proved in Appendix A.

[5] Note that with our assumption of infinitely backlogged traffic, cell-interior users of any BS will always fully utilize the available resources.

Proposition 1. *The condition of changing a user k's RRC from a lower RRC to an upper RRC with the cooperation of BSs 1 and 2 is summarized as follows.*

i) If $C_{1,2}(k) - \overline{C}_1 - \overline{C}_2 < 0$ *and* $C_1(k) - \overline{C}_1 < 0$*, then switching is allowed only if*

$$\overline{C}_1 \cdot C_{1,2}(k) - (\overline{C}_1 + \overline{C}_2) \cdot C_1(k) \geq 0 \tag{14}$$

and if the post-switching ratio $\alpha(k)C_1(k)/C_{1,2}(k)$ *meets the condition (12). The optimal* $\alpha'(k)$*, when these two conditions are met, is given by*

$$\alpha'(k) = \alpha(k)C_1(k)/C_{1,2}(k). \tag{15}$$

ii) If $C_{1,2}(k) - \overline{C}_1 - \overline{C}_2 = 0$ *and* $C_1(k) - \overline{C}_1 < 0$*,* $\alpha'(k)$ *can be chosen arbitrarily subject to (10) and (12).*

iii) If $C_{1,2}(k) - \overline{C}_1 - \overline{C}_2 > 0$ *and* $C_1(k) - \overline{C}_1 \leq 0$*,* $\alpha'(k)$ *should be the maximal available value subject to (10) and (12).*

The case of $C_{1,2}(k) - \overline{C}_1 - \overline{C}_2 > 0$ and $C_1(k) - \overline{C}_1 > 0$ will be separately mentioned at the end of this subsection.

3.2 Downward RRC Switch

Next, we describe a downward RRC switch algorithm, when user k managed by the upper RRC through cooperation between BSs 1 and 2, tries to switch her RRC to a lower RRC managed by cell 1. Also, let $\alpha(k)$ and $\alpha'(k)$ be the resource ratios before and after the switch, respectively. In order to determine the user's throughput post-switching for a given $\alpha'(k)$, the system can use a capacity $C_1(k)$ which is computed using the average SINR reported by user k had she been an interior user in cell 1.

As in the case of upward RRC switch, user k will accept the RRC switch when her throughput becomes higher by changing the RRC. Consequently, the first condition for the downward RRC switch is given by

$$\alpha'(k)C_1(k) - \alpha(k)C_{1,2}(k) \geq 0. \tag{16}$$

Next, the impact of the downward RRC switch on the system throughput depends on the following factors:

- *The throughput gain in cell 2*: The reclassification of user k will release a ratio $\alpha(k)$ of resource in BS 2 which can be distributed to the cell-interior users in BS 2. Thus, the average sum throughput gain by interior users in cell 2 can be quantified as $\alpha(k) \cdot \overline{C}_2$.
- *The throughput change in cell 1*: Notice that if $\alpha'(k) < \alpha(k)$, the residual part $\alpha(k) - \alpha'(k)$ can be distributed to cell 1's interior users who will together achieve an average throughput gain of $(\alpha(k) - \alpha'(k)) \cdot \overline{C}_1$. Otherwise, i.e., if $\alpha'(k) > \alpha(k)$, they will lose an average throughput of $(\alpha'(k) - \alpha(k)) \cdot \overline{C}_1$.
- *System Constraints*: In the case $\alpha'(k) > \alpha(k)$, the additional resource $\alpha'(k) - \alpha(k)$ taken from BS 1 should not jeopardize the minimum throughput requirement of any of its interior users in L_1.

Therefore, a post-switching ratio $\alpha'(k)$ is acceptable only if it leads to an increase in system throughput, i.e., it satisfies

$$\alpha'(k)[C_1(k) - \overline{C}_1] - \alpha(k)[C_{1,2}(k) - \overline{C}_1 - \overline{C}_2] \geq 0, \tag{17}$$

and also respects the system constraints, i.e.,

$$\alpha'(k) \leq 1 - \beta_1 - \sum_{i \in L_1} \frac{T_{\min}(i)}{C_x(i)}. \tag{18}$$

Thus, the optimal ratio $\alpha'(k)$ can be determined by solving the following optimization problem:

$$\begin{aligned} \max \ & \alpha'(k)[C_1(k) - \overline{C}_1] - \alpha(k)[C_{1,2}(k) - \overline{C}_1 - \overline{C}_2] \\ & \text{subject to } (16), (17), \text{ and } (18) \end{aligned} \tag{19}$$

The solution to the above problem is given by the following proposition. The proof is omitted because it is similar to that of the previous proposition corresponding to the upward RRC switch.

Proposition 2. *The conditions for reclassifying a user k and changing her RRC from an upper RRC to a lower RRC is summarized as follows.*

i) If $C_1(k) - \overline{C}_1 < 0$ and $C_{1,2}(k) - \overline{C}_1 - \overline{C}_2 < 0$, then switching is allowed only if

$$(\overline{C}_1 + \overline{C}_2) \cdot C_1(k) - \overline{C}_1 \cdot C_{1,2}(k) > 0, \tag{20}$$

and if the post-switching ratio $\alpha(k)C_{1,2}(k)/C_1(k)$ meets the condition (18). The optimal $\alpha'(k)$, when these two conditions are met, is given by

$$\alpha'(k) = \alpha(k)C_{1,2}(k)/C_1(k). \tag{21}$$

ii) If $C_1(k) - \overline{C}_1 = 0$ and $C_{1,2}(k) - \overline{C}_1 - \overline{C}_2 < 0$, $\alpha'(k)$ can be chosen arbitrarily subject to (16) and (18).

iii) If $C_1(k) - \overline{C}_1 > 0$ and $C_{1,2}(k) - \overline{C}_1 - \overline{C}_2 \leq 0$, $\alpha'(k)$ should be the maximal possible value subject to (16) and (18).

Remark 1. The case of $C_1(k) - \overline{C}_1 > 0$ and $C_{1,2}(k) - \overline{C}_1 - \overline{C}_2 > 0$ can be considered in both upward and downward switchings, where $\alpha'(k)$ should be the maximal possible value subject to other constraints. Suppose user k in cell 1 is served by a lower RRC and satisfies $C_1(k) - \overline{C}_1 > 0$ and $C_{1,2}(k) - \overline{C}_1 - \overline{C}_2 > 0$. Then, if upward switching is permitted, the user will seek a maximal $\alpha'(k)$ subject to the other conditions required for the upward RRC switch. Upon switching, the user will then try to switch to a lower RRC, again seeking a maximal $\alpha'(k)$ subject to the other conditions required for the downward RRC switch. It can be verified that an upward (third) switch will be not possible and the same observation holds if the user were originally served by the upper RRC. Thus, users satisfying $C_1(k) - \overline{C}_1 > 0$ and $C_{1,2}(k) - \overline{C}_1 - \overline{C}_2 > 0$ may switch at most twice, and in our simulation, such users are observed to mainly remain in the lower RRC.

Remark 2. We now justify the extra condition we imposed that a user's throughput must not decrease upon switching, instead of just requiring an increase in system throughput for switching, where the latter will be referred to as relaxed switching in the sequel. This additional constraint ensures better cell-edge performance by protecting cell edge users against loss in throughput. Consider the upward switch of a user in cell 1 and assume that an upward switch is possible in relaxed upward switching but not in our switching. In this case, with upward relaxed switching, the system can decide to reclassify an interior user with a lower average capacity as a cell-edge user and allocate a resource ratio just enough to meet its minimum throughput. Moreover, the increase in system throughput in this case is due to an increase in the sum throughput of cell 1's other interior users. A similar observation holds for the downward switch case. Thus the additional constraint prevents the system from using switching to boost system throughput by starving edge users.

3.3 Simplified Solutions

We now develop simplified solutions for both the RRC switch algorithms when the capacity of an interior user can be computed using eq. (1). We make the assumption that in order to be eligible for switching a user must satisfy $C_1(k) < \overline{C}_1$ as well as $C_{1,2}(k) < \overline{C}_1 + \overline{C}_2$. Note that this assumption is reasonable since the average capacity of a user k at the edge of cell 1 will be smaller than the average per-user capacity of the cell-interior users and is validated in our simulation. As a consequence, only the first cases in both *Propositions 1* and *2* are now possible and we address them below.

Fractional frequency reuse. Suppose fractional frequency reuse is employed to support the cell-edge users. Now consider the upward RRC switch. Using the capacity expression given in eq. (3), the condition in (14) can be expressed as

$$\overline{C}_1 \log(1+\gamma_1) - (\overline{C}_1 + \overline{C}_2) \log\left(1 + \frac{\gamma_1}{\gamma_2 + 1}\right) \geq 0. \tag{22}$$

The above expression in turn can be compactly written as

$$(1+\gamma_1)(1+\gamma_2)^{1+\lambda} \geq (1+\gamma_1+\gamma_2)^{1+\lambda}, \tag{23}$$

where $\lambda = \overline{C}_2/\overline{C}_1$. Similarly, it can be shown that the corresponding condition for the downward RRC switch is given by (23) but where the inequality is reversed.

Macro-diversity. Next, when macro-diversity is employed to support the cell-edge users, using the capacity expression given in eq. (5), the condition (14) in the upward RRC switch can be expressed as

$$\overline{C}_1 \log(1+\gamma_1+\gamma_2) - (\overline{C}_1 + \overline{C}_2) \log\left(1 + \frac{\gamma_1}{\gamma_2 + 1}\right) \geq 0. \tag{24}$$

This can be further rewritten as

$$(1+\gamma_2)^{1+\lambda} \geq (1+\gamma_1+\gamma_2)^{\lambda}. \quad (25)$$

The corresponding condition for the downward RRC switch is given by (25) but where the inequality is reversed.

Therefore, in order to decide the RRC switch using the simplified conditions, each user can report γ_1 and γ_2 to the admission controller, and the admission controller should be able to determine λ. The role of γ_1, γ_2 and λ is highlighted in the following proposition.

Proposition 3. *An upward RRC switch requires an increasing value of γ_2 as λ increases, given an arbitrarily fixed γ_1. Conversely, a downward RRC switch requires a decreasing value of γ_1 as λ increases, given an arbitrarily fixed γ_2.*

The proof is given in Appendix B.

Fig. 1 depicts the boundary conditions of switching a RRC as a function of γ_1 and γ_2 as given by (23) and (25) for fractional frequency reuse and macro-diversity, respectively. As stated in *Proposition 3*, a greater γ_2 is needed for an upward switch when λ is higher.

Thus far, we have assumed that the average capacity of the interior users in a neighboring cell is available. When this information is unavailable in the network, or each user (instead of an admission controller) independently wants to decide the RRC switch without network-level information, we can obtain approximate conditions assuming $\lambda = 1$ (i.e., $\overline{C}_1 = \overline{C}_2$). Then the conditions of (14) and (20) are simply expressed by

$$C_{1,2}(k) - 2C_1(k) \geq 0 \text{ and } C_{1,2}(k) - 2C_1(k) < 0. \quad (26)$$

Specifically, in the case of macro-diversity, the boundary condition in (25) is given by

$$\gamma_2 = \frac{(1+4\gamma_1)^{1/2} - 1}{2}, \quad (27)$$

which provides an insight for designing *H_Add Threshold* and *H_Delete Threshold* for *macro diversity hand-off procedure* defined in the IEEE 802.16e standard [11].[6]

3.4 Overhead of RRC Switch

Throughout this paper, we consider stationary (fixed or nomadic) users. Fast-moving users can always be managed by the upper RRC regardless of whether

[6] The IEEE 802.16e standard introduces a macro diversity hand-off procedure where a mobile user is able to transmit or receive unicast messages and traffic from multiple BSs at the same time interval. According to [11], when the long-term SINR of a serving BS is less than *H_Delete Threshold*, the mobile station shall send MOB_MSHO-REQ to require dropping this serving BS from the diversity set, and when the long-term SINR of a neighboring BS is higher than *H_Add Threshold*, the mobile station shall send MOB_MSHO-REQ to require adding this neighbor BS to the diversity set.

they are classified as cell-interior or cell-edge users, but we do not consider such mobility issues here. Stationary users compute γ_1 and γ_2 via a long-term average, so most users will not suffer from frequent RRC switch. The overhead of RRC switch is the exchange of signaling messages for switch request and response between two RRCs. If the algorithms are triggered more frequently, the classification will probably be more accurate, but the overhead will be higher.

4 Simulation Results

We evaluated the performance in an OFDMA-based wireless network by simulation experiments, emulating mobile WiMAX systems with parameters listed in Table 1. We consider a single omnidirectional antenna at each transmitter and each receiver. In our simulator, users are uniformly distributed in a hexagonal cell and BSs of 6 first-tier and 12 second-tier neighboring cells generate intercell interference to those users. Our channel model follows path loss with an exponent of 4, Gaussian shadowing with zero mean and variance of 8 dB, and Rayleigh fading. We use the Jakes' model [13] to generate frequency-selective Rayleigh fading followed by the Doppler effect with the maximum velocity of 3 Km/hr. To serve cell-interior users, BSs either adopt a round-robin (RR) scheduling algorithm or a multi-channel proportional fair (PF) scheduling algorithm [14] that guarantees minimum throughput (150 Kbps for all users in our setting) [10]. It is assumed that the channel coefficients are perfectly known at the BS and the data rate is then determined by the Shannon capacity. In our simulation, each user measures the two strongest γ's from her neighboring BSs, and the serving BS is able to coordinate with one or two of those neighboring BSs. The cell performance was computed during the simulation time of 60 seconds, after each user's RRC had been completely determined according to our algorithm.

Our simulation results show that users are appropriately classified into cell-edge and cell-interior types by our algorithms. We confirmed that i) the first cases in *Propositions 1* and *2* are generally observed, ii) FFR and macro-diversity (MD) increase cell-edge throughput by up to 15% when $\lambda = 1$ without a loss in system throughput, and iii) more users switch to the cell-edge type when the neighboring cell is lightly loaded.

First, Fig. 2 shows the distribution of cell-edge users' γ_1 and γ_2 in the case of Fig. 1, when macro-diversity by at most two BSs is employed and $\overline{C}_1 = \overline{C}_2$. The black area represents γ_1 and γ_2 of those users by simulation results and two lines

Table 1. Parameters for simulation [12]

Channel bandwidth	5 MHz	No. of sub-channels	8
Carrier frequency	2.3 GHz	TX power at BSs	43 dBm
Cell radius	1 Km	Path loss exp.	4
Shadowing var.	8 dB	Max. Doppler vel.	3 Km/hr
Number of users	30	$T_{\min}(i)$	150 Kbps
Simulation time	60 seconds	No. of simulations	1000

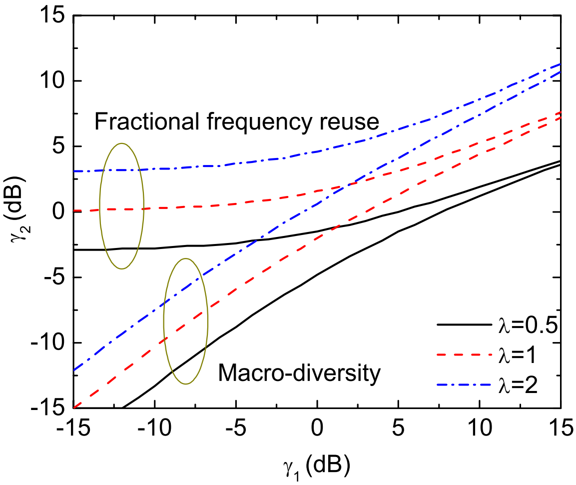

Fig. 1. Boundary conditions of switching a RRC

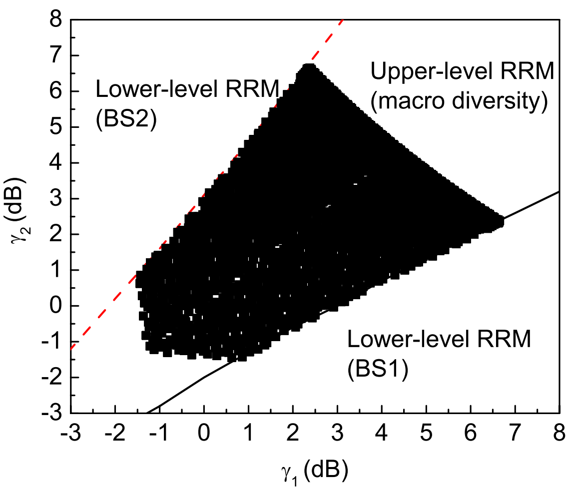

Fig. 2. Distribution of cell-edge users' γ_1 and γ_2 when macro-diversity is used and $\overline{C}_1 = \overline{C}_2$

represent the threshold given by (14). In this experiment, the other cases except the first one in *Propositions 1* and *2* are rarely observed; for instance, the ratio of such cases is only 0.5% among all users at $\lambda = 0.2$ and it approaches zero as

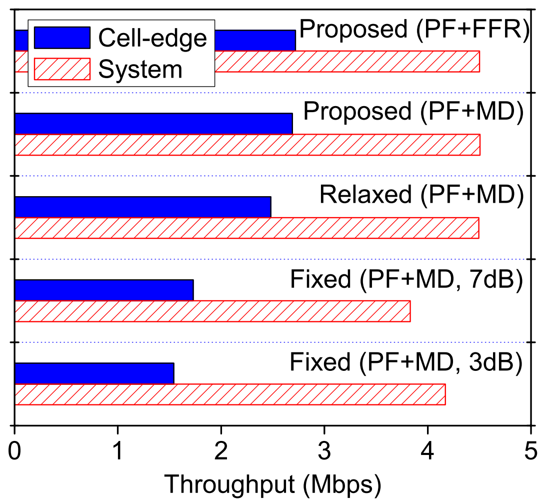

Fig. 3. Comparison of cell-edge users' average throughput and system throughput in various mechanisms

λ increases above 0.2. Therefore, as expected, the first cases can be regarded as the simplified solution in general.

The average cell-edge throughput and system throughput (i.e., cell throughput in this simulation) are presented in Fig. 3 when $\lambda = 1$. Both "PF+FFR" and "PF+MD" represent the cases where cell-interior users are supported by the PF scheduling and cell-edge users are supported by FFR or MD. The proposed algorithm shows better cell-edge throughput, compared to the relaxed switching ("Relaxed") mentioned in *Remark 2*. Compared to the case of no upper RRC, the proposed one improves cell-edge throughput by 13.0% and 14.3% for FFR and MD, respectively, without a loss in system throughput, while the relaxed case improves it only by 4.2%. Also, our algorithm is compared to a simple mechanism (represented by "Fixed") where RRC switch is determined by a fixed threshold, $\gamma_1 - \gamma_2$ (3dB or 7dB). Here γ_2 is given by the neighboring BS that interferes most dominantly. In summary, the proposed algorithm achieves the best cell-edge throughput without losing system throughput. We omit "PF+FFR" for the fixed and relaxed switching because it results in a slightly inferior cell-edge performance to "PF+MD".

The effect of λ is demonstrated in Fig. 4 that plots β as a function of λ. Here, β also includes the fraction of resource allocated to cell-edge users who are located in six neighboring cells. As discussed in *Proposition 3*, users are less likely to switch to the upper RRC as λ increases. To obtain this result, we imposed no upper limit on β (i.e., $\beta_{\max} = 1$). When RR scheduling is employed for cell-interior users, they do not take advantage of opportunistic scheduling,

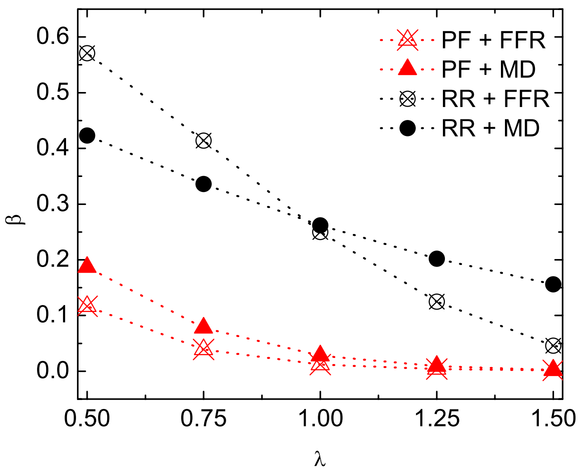

Fig. 4. β vs. λ

and thus it drives more users to switch to the upper RRC. Therefore, β in case of RR scheduling is much greater than that of PF scheduling.

5 Conclusion

We have proposed a new RRM framework for wide-area wireless data networks that manages radio resources of cell-interior and cell-edge users separately. The work presented in this paper has been limited to downlink data transmission; RRM schemes for uplink in conjunction with downlink would be one avenue for future work.

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A Appendix: Proof of Proposition 1

In the case of i), the RRC switch is possible if an $\alpha'(k)$ exists such that

$$\alpha(k)\frac{C_1(k)}{C_{1,2}(k)} \leq \alpha'(k) \leq \alpha(k)\frac{\overline{C}_1 - C_1(k)}{\overline{C}_1 + \overline{C}_2 - C_{1,2}(k)}, \tag{28}$$

which is obtained from (10) and (11). The upper bound must be greater than the lower bound, which results in (14). The objective is maximized by the minimal value, i.e., $\alpha'(k) = \alpha(k)C_1(k)/C_{1,2}(k)$. The proofs of the other cases are omitted because they follow along similar lines.

B Appendix: Proof of Proposition 3

For brevity, we only prove the case of upward switching. In the case of fractional frequency reuse, (23) is equivalent to

$$\lambda < \frac{\log(1+\gamma_1)}{\log(1+\gamma_1/(\gamma_2+1))} - 1 \triangleq f(\gamma_2) \tag{29}$$

In the case of macro-diversity, (25) can be re-written as

$$\lambda < \frac{1}{1 - \frac{\log(1+\gamma_2)}{\log(1+\gamma_1+\gamma_2)}} - 1 \triangleq g(\gamma_2) \tag{30}$$

It is easily proved that for a fixed γ_1, $f(\gamma_2)$ and $g(\gamma_2)$ are monotonically increasing functions of γ_2. Therefore, as the average capacity of a neighboring cell 2 increases (i.e. as λ increases), an increasing value of γ_2 is required.