A Simple Scheduling Restriction Scheme for Interference Coordinated Networks

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***Abstract*— Scheduling restriction is attracting much attention in LTE-Advanced as a technique to reduce power consumption and network overhead in interference coordinated heterogeneous networks (HetNets). Such a network with inter-cell interference coordination (ICIC) provides two radio resources with different channel quality statistics. One of the resources is protected (unprotected) from inter-cell interference (hence, called protected (non-protected) resource) and has higher (lower) average channel quality. Without scheduling restriction, the channel quality feedbacks would be doubled to reflect such quality difference of the two resources. We present a simple scheduling restriction scheme that addresses the problem without significant performance degradation. Users with relatively larger (smaller) average channel quality difference between the two resources are scheduled in the protected (non-protected) resource only, and a boundary user, determined by a proportional fair resource allocation (PFRA) under simplified static channels, is scheduled on either of the two resources or both depending on PFRA. Having most users scheduled in only one of the resources, power consumption and network overheads that would otherwise be required for the channel quality feedbacks on the other resource can be avoided. System level simulation of LTE-Advanced downlink shows that the performance degradation due to our scheduling restriction scheme is less than 2%, with the average feedback reduction of 40%.**

Keywords- scheduling restriction; inter-cell interference coordination (ICIC); Long-Term Evolution (LTE)-Advanced; heterogeneous network (HetNet); proportional fair

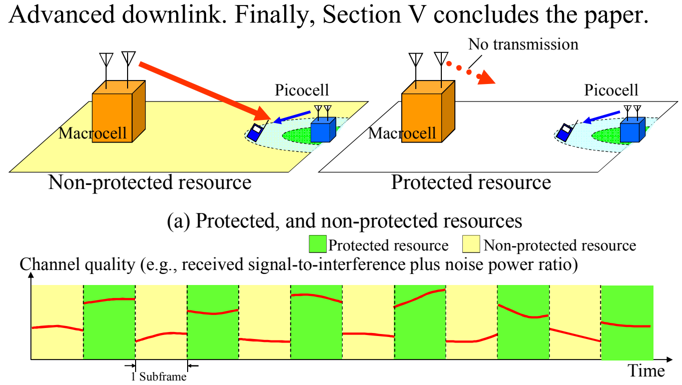
I. INTRODUCTION

Channel quality feedback plays an essential role in a number of performance improvement techniques of wireless communication. A certain amount of channel feedback is, therefore, inevitable. However, measurement and network transport of channel feedbacks consume limited wireless resources such as battery and bandwidth, which otherwise could be used for user data. Further, compared to user data, channel feedback consumes more resource per bit since transmitted typically on the control channel using low modulation and heavy coding for robustness. Thus, it is important to reduce channel feedbacks, while meeting performance requirements.

In Long-Term Evolution (LTE)-Advanced, inter-cell interference coordination (ICIC), in combination with heterogeneous network (HetNet) deployment is known to improve the system and cell-edge throughputs [1][4]. In such a network, low power small cells such as picocells are overlaid onto traditional high power macrocells, which stop transmission for a specific frequency or time resource ("protected resource") to protect the users connected to the picocells, and transmit only on the other type of resource ("non-protected resource") as shown in Fig. 1(a). On the other hand, the picocells do not need to stop transmission, since the interference from the picocells is not a problem due to the smaller transmission power. Therefore, from a picocell user's perspective, the protected (non-protected) resource is of higher (lower) channel quality (See Fig. 1(b) for an example). This suggests a significant increase of channel quality feedbacks in picocells because separate feedback is necessary for each resource to reflect such quality difference.

We present a simple scheduling restriction scheme that assigns only either of the resources to each user, except for at most one user. The users assigned to only one of the resources are required to feedback channel quality of that resource only, which significantly reduces channel feedbacks. In order to determine which resources to be used for each user, all users report the channel quality of both resources "averaged" in frequency-domain with relatively large reporting period (hence "sampled" in time domain). Then scheduling restriction for the picocell is determined according to proportional fair resource allocation (PFRA) under the simplified static channels derived from the above averaged and sampled channel qualities.

The rest of the paper is organized as follows. In Section II, we discuss scheduling restriction design. Section III presents details of restricted scheduling under multipath fading channels, and discusses its impacts on performance and feedback, which are verified in Section IV by system level simulation for LTE-Advanced downlink. Finally, Section V concludes the paper.



(b) Different channel quality

Figure 1. Interference coordinated system.

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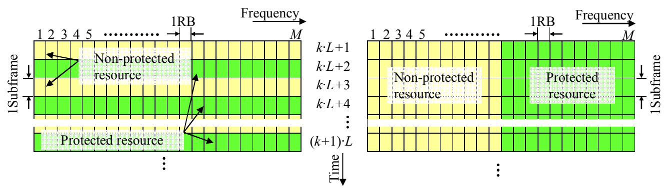

(a) Time-domain (b) Frequency-domain

Figure 2. Inter-cell Interference coordination

II. SCHEDULING RESTRICTION DESIGN

A. Problem Description

Fig. 2 shows an example of a resource, R_k, which comprises M resource blocks (RBs) in frequency domain and L subframes in time domain starting from ($k\cdot L$+1)-th subframe (k is an integer). The resource R_k is partitioned in time or frequency domain as a result of ICIC, defining protected and non-protected resources. The minimum assignment unit is an RB in a subframe. Denote m-th RB in l-th subframe as (l, m), and let $R_{p,k}=\{(l, m)\in R_k$ *that belongs to protected resource*$\}$ and $R_{np,k}=\{(l, m)\in R_k$ *that belongs to non-protected resource*$\}$. Denote the total numbers of protected and non-protected RBs in the resource R_k as $B_{p,k}$ and $B_{np,k}$, respectively. Then, $B_{p,k}= |R_{p,k}|$, $B_{np,k}= |R_{np,k}|$, and $B_{p,k} + B_{np,k} = LM$, where $|A|$ is the cardinality of a set A. Although not shown in Fig. 2, $R_{p,k+1}$ and $R_{np,k+1}$ may or may not be the same as $R_{p,k}$ and $R_{np,k}$, respectively. Hereafter, we omit the subscript k in the subsequent notations unless needed. The scheduling restriction, if employed, is assumed to be updated every L subframes.

Without scheduling restriction, proportional fair scheduler (PFS) [3][8] operates as follows [6]:

- User selection

$$n^*(l,m) = \arg\max_{n\in\{1,2,\ldots,N\}} \left(\frac{r(l,m,n)}{\mu(l,n)}\right) \quad \textbf{(1)}$$

- Resource assignment

$$b(l,m,n) = \begin{cases} 1, & if\ n = n^*(l,m) \\ 0, & otherwise \end{cases} \quad \textbf{(2)}$$

- Average rate update

$$\mu(l+1,n) = (1-\varepsilon)\cdot\mu(l,n) + \frac{\varepsilon}{M}\sum_{m=1}^{M} r(l,m,n)\cdot b(l,m,n) \quad \textbf{(3)}$$

where, $n^*(l,m)$ is the user index as scheduled by (1) at (l,m), $r(l,m,n)$ represents data rate achieved for n-th user at (l,m), $\mu(l,n)$ is the average throughput of the user n at the l-th subframe, $0\leq\varepsilon\leq 1$ is an averaging constant, and $b(l,m,n)$ represents assignment of user n at (l, m). In other words,

$$b(l,m,n) = \begin{cases} 1, & if\ user\ n\ is\ assigned\ at\ (l,m) \\ 0, & if\ user\ n\ is\ not\ assigned\ at\ (l,m). \end{cases} \quad \textbf{(4)}$$

With scheduling restriction, on the other hand, users n=1,2,…,N in a cell are partitioned into three sets of users: $S_p=\{$*users scheduled in* R_p *only*$\}$, $S_{np}=\{$*users scheduled in* R_{np} *only*$\}$, $S_{pnp}=\{$*users scheduled in both* R_p *and* $R_{np}\}$, and the user selection operation of PFS for R_p *and* R_{np} are respectively restricted to the subset of users, i.e. $(S_p \cup S_{pnp})$ and $(S_{np} \cup S_{pnp})$.

- User selection

$$n^*(l,m) = \begin{cases} \arg\max_{n\in(S_p\cup S_{pnp})} \left(\frac{r(l,m,n)}{\mu(l,n)}\right), & if\ (l,m)\in R_p \\ \arg\max_{n\in(S_{np}\cup S_{pnp})} \left(\frac{r(l,m,n)}{\mu(l,n)}\right), & if\ (l,m)\in R_{np} \end{cases} \quad \textbf{(5)}$$

We are interested in a scheduling restriction scheme (i.e. a user partition, S_p, S_{np}, and S_{pnp}) that satisfies the following two requirements:

- Performance requirement

Due to the loss of freedom of allocating the resource other than allowed by the restriction, the performance of restricted scheduling (with $|S_{pnp}| < N$) may be worse than that of scheduling without restriction. Scheduling restriction should not cause significant performance degradation.

- Feedback requirement

Channel quality feedbacks can be reduced by making more users to be scheduled in only one of the two resources. Scheduling restriction that suppresses $|S_{pnp}|$ as small as possible is desirable.

Clearly there is a tradeoff between performance and feedback. The goal of scheduling restriction design is to make good tradeoff between the two requirements.

B. Scheduling Restriction without Performance Degradation

Let $b_{SR}(l,m,n)$ and $b_{NR}(l,m,n)$ respectively represent assignment of user n at (l, m) by a scheduler with and without restriction, (here, SR and NR stand for "schedulig restriction" and "no restriction," respectively). Suppose $b_{NR}(l,m,n)$ is known a priori. If there is a user, n, such that

$$\forall(l,m)\in R_{np},\ b_{NR}(l,m,n)=0, \quad \textbf{(6)}$$

then regardless of whether $n\in S_p$ or $n\in S_{pnp}$,

$$\forall(l,m)\in R,\ b_{NR}(l,m,n)=b_{SR}(l,m,n). \quad \textbf{(7)}$$

This means scheduling restriction with $n\in S_p$ does not involve any changes in scheduling behavior; hence no performance degradation. Similarly, if there is a user, n, such that

$$\forall(l,m)\in R_p,\ b_{NR}(l,m,n)=0, \quad \textbf{(8)}$$

then scheduling restriction with $n\in S_{np}$ does not incur any performance degradation. Hereafter, the scheduling restriction scheme obtained from a priori knowledge of $b_{NR}(l,m,n)$ is denoted as SR(PP) (here, PP stands for "perfect prediction").

SR(PP) is desirable in that there is no performance degradation. But it is not useful for LTE-Advanced and in practice due to the problems explained below.

Firstly, a priori knowledge of $b_{NR}(l,m,n)$ is not available. Scheduling behavior of PFS under multipath fading channel depends on the statistics of $r(l,m,n)$. Closed form analysis of PFS under multipath fading channel has been reported for one type of resource, assuming exponential or Gaussian rate distribution [7], which does not comply with LTE-Advanced model [8]. Furthermore, to the best of our knowledge, there is no closed from solution reported for two types of resources with different channel statistics, even assuming exponential or Gaussian rate distribution.

Secondly, according to our simulation under LTE-Advanced model [8], PFS turns out to schedule 89% of users of picocells with $N\geq 2$ to both R_p and R_{np} (i.e. $|S_{pnp}|\approx 0.89\cdot N$). Thus we argue that even with a priori knowledge of $b_{NR}(l,m,n)$, SR(PP) does not serve as a good scheduling restriction scheme because the feedback requirement would be unsatisfied. This issue is revisited later with a simulation result in Section IV.C.

C. PFRA-based Scheduling Restriction

As stated earlier, the design goal of scheduling restriction is to make good tradeoff between performance and feedback requirements. Toward that goal, we use proportional fair resource allocation (PFRA) under simplified static channels. Under simplified static channels, for each user n, $r(l,m,n)$ is represented by two constants:

$$r(l,m,n)=\begin{cases} r_p(n), & \forall (l,m)\in R_p \\ r_{np}(n), & \forall (l,m)\in R_{np} \end{cases} \quad \textbf{(9)}$$

where, $r_p(n)$ and $r_{np}(n)$ may be an "average" (or "sample") rate of the user n over R_p and R_{np}, respectively.

Then throughput distribution of N users, $\{x(n), n = 1, 2, ..., N\}$, is proportional fair [5], if it maximizes the objective function given by

$$f=\frac{1}{N}\sum_{n=1}^{N}\log(x(n))=\frac{1}{N}\sum_{n=1}^{N}\log\left(\frac{1}{LM}\left(r_p(n)\cdot b_p(n)+r_{np}(n)\cdot b_{np}(n)\right)\right) \quad \textbf{(10)}$$

where

$$b_p(n)=\sum_{(l,m)\in R_p} b(l,m,n) \quad \textbf{(11)}$$

$$b_{np}(n)=\sum_{(l,m)\in R_{np}} b(l,m,n). \quad \textbf{(12)}$$

Without loss of generality, for n=1,2,…,N–1,

$$d(n)=\frac{B_p}{B_{np}}\cdot\frac{r_p(n)}{r_{np}(n)}\geq d(n+1) \quad \textbf{(13)}$$

which means the users are sorted in the order of decreasing channel quality difference. We assume there is no user n such that $r_p(n)=r_{np}(n)=0$ because in practice such a user is prevented by appropriate cell selection and network planning. Owing to this assumption, $d(n)$ is defined for all users. Due to ICIC, the data rate of protected resource is better than that of non-protected resource. Therefore, $r_p(n)\geq r_{np}(n)$, i.e. $d(n)\geq B_p/B_{np}>0$. There are cases where trivial solutions exist that maximize f.

- If $\forall n$, $r_{np}(n)=0$, then PFRA is effectively for R_p only, and the trivial solution is $b_p(n)=B_p/N$. So we assume there is at least a user satisfying $r_{np}(n)>0$. From (13), these conditions can be expressed as

$$d(N)<\infty. \quad \textbf{(14)}$$

- If there is one user in a cell, i.e., N=1, PFRA is to schedule the user in both resources. In other words, scheduling restriction is unnecessary. So, we assume $N\geq 2$.

With the above assumptions, it can be shown that the solution that maximizes f is given by

$$\begin{cases} b_p(n)=\dfrac{B_p}{\lambda_p},\ b_{np}(n)=0, & if\ n=1,...,K \\ b_p(n)=B_p\cdot\dfrac{\alpha}{\lambda_p},\ b_{np}(n)=B_{np}\cdot\dfrac{1-\alpha}{\lambda_{np}}, & if\ n=K+1 \\ b_p(n)=0,\ b_{np}(n)=\dfrac{B_{np}}{\lambda_{np}}, & if\ n=K+2,...,N \end{cases} \quad \textbf{(15)}$$

where $K\in\{0,1,\ldots,N-1\}$, such that

$$G(d(K+1))-1\leq K<G(d(K)) \quad \textbf{(16)}$$

with $G(x) = N\cdot x/(1+x)$ for $x\geq 0$, and

$$\lambda_p=\max(G(d(K+1)),K) \quad \textbf{(17)}$$

$$\lambda_{np}=N-\lambda_p \quad \textbf{(18)}$$

$$\alpha=\lambda_p-K. \quad \textbf{(19)}$$

Due to space limitation, the derivation of the above solution is not provided. We set $d(0)=\infty$ in (16) for non-existing user with n=0.

By (4), $b(l,m,n)\geq 0$. So, if $b_{np}(n)=0$ ($b_p(n)=0$), then $\forall (l,m)\in R_{np}$, $b(l,m,n)=0$ ($\forall (l,m)\in R_p$, $b(l,m,n)=0$). Then by (6), (8), and (15)

$$\begin{cases} n\in S_p, & if\ n=1,...,K \\ n\in S_{np}, & if\ n=K+2,...,N. \end{cases} \quad \textbf{(20)}$$

Only the user with $n=K+1$ is assigned to both resources if $0<\alpha<1$. The user is assigned to either of the two resources if α=0 or 1. From (16), (17) and (19)

$$n=K+1\in\begin{cases} S_p, & if\ G\left(d\left(K+1\right)\right)=K+1 \\ S_{pnp}, & if\ K<G\left(d\left(K+1\right)\right)<K+1 \\ S_{np}, & if\ G\left(d\left(K+1\right)\right)\leq K. \end{cases} \quad \textbf{(21)}$$

From the above, regardless of N

$$\left|S_{pnp}\right|=0\ or\ 1. \quad \textbf{(22)}$$

III. PFRA-BASED RESTRICTED SCHEDULING

In this section, the details of the scheduling with PFRA-based scheduling restriction are described.

A. Simplification of Multipath Fading Channel

An example is discussed hereafter assuming the time-domain ICIC in Fig. 2(a), although it can be extended to other cases. The wideband channel quality, which represents the instantaneous data rate averaged over entire bandwidth for both resources are assumed to be obtained. In the time domain, the wideband channel qualities for protected and unprotected subframes are sampled in every L subframes. For example, the wideband channel qualities of R_k are obtained from the last two subframes of the R_{k-1}, as expressed by

$$r_{np,k}(n) = \frac{1}{M}\sum_{m=1}^{M} r(k \cdot L-1, m, n), \quad \textbf{(23)}$$

$$r_{p,k}(n) = \frac{1}{M}\sum_{m=1}^{M} r(k \cdot L, m, n). \quad \textbf{(24)}$$

Note that although instantaneous data rate in one subframe is used in (23) and (24), it is possible to average in time domain by employing averaging constant.

B. PFRA-based Restricted PFS

TABLE I shows the algorithm for determining PFRA-based scheduling restriction. The data rates as in (23) and (24) are made available to scheduler and plugged to (13) to derive $d(n)$. Based on $d(n)$, the scheduling restriction (i.e., S_p, S_{np}, and S_{pnp}) is determined by (20) and (21), and is communicated to users. Then, users provide the scheduler with the channel quality for individual RBs (i.e. $r(l,m,n)$) only for the resources as allowed by the restriction. According to the scheduling restriction and the channel quality for individual RBs, the PFS scheduling operations as in (2), (3), and (5) are executed.

C. Performance Impacts

The benefit from user diversity is reduced because the scheduling is restricted to the subset of users, i.e. $(S_p \cup S_{pnp})$ or $(S_{np} \cup S_{pnp})$ as in (5). Since based on PFRA-based restriction, however, the restricted PFS has following properties that positively impact performance:

- Users at cell edge restricted to R_p

From (13) and (20), the channel quality difference between R_p and R_{np} is relatively larger for the users with n=1,2,…,K than for the users with n=K+2,…,N. This implies the users with n=1,2,…,K are most likely at the cell edge, with the channel quality of R_{np} experiencing larger degradation by the macrocell interference. Assigning those users only in R_p improves the user throughputs of those users (hence fairness) with more efficiency (when compared with an alternative of assigning R_{np}).

TABLE I. PFRA-BASED SCHEDULING RESTRICTION ALGORITHM

1. sort $d(n)$ in descending order.
2. **if** $d(N) = \infty$, **then**
   S_p= {1, 2, …, N} and $S_{np} = S_{pnp} = \phi$.
3. **else if** N = 1, **then**
   $S_p = S_{np} = \phi$ and S_{pnp}= {1}.
4. **else**
   find $K \in$ {0, 1, …, N–1}, which satisfies $G(d(K+1)) - 1 \le K < G(d(K))$.
   if $G(d(K+1)) = K + 1$, **then**
   S_p= {1, 2, …, K+1}, S_{np}= {K+2, …, N} and S_{pnp}= ϕ.
   else if $K < G(d(K+1)) < K+1$, **then**
   S_p= {1, 2, …, K}, S_{np}= {K+2, …, N} and S_{pnp}={K+1}.
   else if $G(d(K+1)) \le K$, **then**
   S_p= {1, 2, …, K}, S_{np}= {K+1, …, N} and S_{pnp}= ϕ.
   endif
5. **endif**

- Users at vicinity of cell site restricted to R_{np}

Similarly from (13) and (20), the users with n=K+2,…,N are most likely located at the vicinity of the cell site, with the channel quality of R_{np} experiencing smaller degradation by the macrocell interference. The loss of the user throughput by assigning those users only in R_{np} is less prominent due to small channel quality difference between R_p and R_{np}. That way, the lower quality resource, R_{np}, is efficiently used, contributing to the system throughput improvement.

- Adaptive boundary

From (13) and (16), the boundary user with n=K+1 is determined based on the number of users, N, the rate distributions of the users, $r_p(n)$ and $r_{np}(n)$, and the size of the two resources, B_p and B_{np}, so that the throughput distribution as in (10) is proportional fair. Therefore, various scenarios that may happen in practice with any changes in the above are dealt with adaptively but in a consistent way by PFRA-based scheduling restriction.

D. Feedback Impacts

In this section, feedback reduction by the proposed scheduling restriction is discussed. Denote, as N_{SC} and N_{SR}, the total number of channel quality feedbacks required for scheduling and scheduling restriction for R, respectively. Recall the numbers of channel quality feedbacks for individual RBs in R_p and R_{np} are B_p and B_{np}, respectively. Without scheduling restriction, all users generate B_p+B_{np}=LM number of channel quality feedbacks for individual RBs (i.e. $r(l,m,n)$) for scheduling, but does not generate wideband channel quality feedbacks (i.e. $r_p(n)$, $r_{np}(n)$) that are used for scheduling restriction. Hence,

$$N_{SC} = LMN, \quad \textbf{(25)}$$

$$N_{SR} = 0. \quad \textbf{(26)}$$

With scheduling restriction, on the other hand, users generate feedbacks only for the resource(s) as allowed by the restriction, which is given by

$$N_{SC} = B_p\left|S_p\right| + B_{np}\left|S_{np}\right| + LM\left|S_{pnp}\right|. \quad \textbf{(27)}$$

Instead, each user provides the wideband channel quality for R_p and R_{np} once in every L frames. Thus,

$$N_{SR} = 2N. \quad \textbf{(28)}$$

Assume that $r_p(n)$, $r_{np}(n)$ and $r(l,m,n)$ are quantized using Q bits. A scheduling restriction update for a user needs 2 bits to indicate one of the following: S_p, S_{np} and S_{pnp}. So the scheduling restriction update requires up to $2 \cdot N$ bits once in every L subframes.

Denote, as O_{SR} and O_{NR}, the number of overhead bits for scheduling with and without restriction, respectively. Then,

$$O_{NR} = QLMN, \quad \textbf{(29)}$$

$$O_{SR} = Q\left(B_p\left|S_p\right| + B_{np}\left|S_{np}\right| + LM\left|S_{pnp}\right| + 2N\right) + 2N. \quad \textbf{(30)}$$

To quantify overhead reduction, define the overhead ratio as

$$\frac{O_{SR}}{O_{NR}} = \frac{B_p\left|S_p\right| + B_{np}\left|S_{np}\right| + LM\left|S_{pnp}\right| + 2N}{LMN} + \frac{2}{QLM}. \quad \textbf{(31)}$$

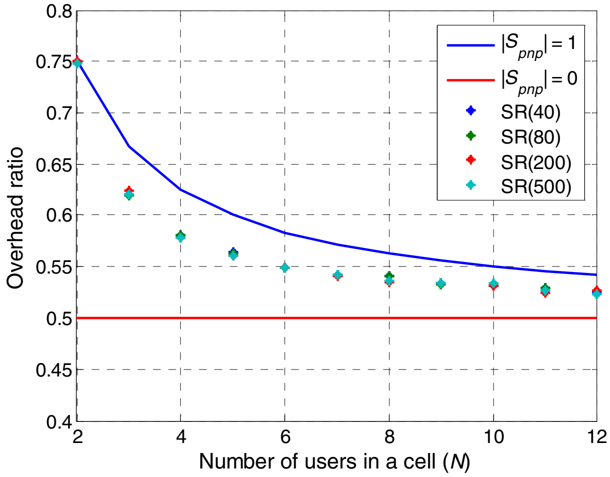

Figure 3. Overhead ratio distribution

If $B_p = B_{np} = LM/2$ as in Section IV,

$$\frac{O_{SR}}{O_{NR}} = \frac{1}{2} + \frac{|S_{pnp}|}{2N} + \frac{2}{LM} + \frac{2}{QLM}. \qquad \textbf{(32)}$$

With sufficiently large L, M and N, $O_{SR}/O_{NR} \approx 1/2$. Fig. 3 shows O_{SR}/O_{NR} plotted for $|S_{pnp}|=0$ and $|S_{pnp}|=1$ for a range of N, assuming $L=40$, $M=50$, and $Q=4$.

IV. Verification

A. Simulation Configuration

The validity of the restricted scheduling in Section III is investigated by system level simulation, using the time-domain resource partitioning as in Fig. 2(a) employed over 2,000 subframes. $M=50$ and L, which should not be less than 40 according to [2], is chosen from {40, 80, 200, 500}. R_p and R_{np} comprise all RBs of even-numbered subframes and odd-numbered subframes of R, respectively. With L being an even number, a half of the resource is used for R_p and the other half for R_{np}, i.e., $B_p=B_{np}$.

According to [8], we employed a 19-hexagonal macrocell model with 3 sectors per cell. We assume that four picocells are randomly located within each sector with a uniform distribution. The cell radius of the macrocells is set to 289 m. The locations of the 25 users in each sector of the macrocells are assigned randomly with a uniform distribution. In the propagation model, we take into account distance-dependent path loss with the decay factor of 3.76 (3.67), lognormal shadowing with the standard deviation of 8 dB (10 dB) for the macro (pico) cell, and instantaneous multipath fading. It is assumed that the distance-dependent path loss and shadowing are constant, while the time-varying instantaneous fading variations are added in the performance measurement. The shadowing correlation between the cells (sectors) is set to 0.5 (1.0). The 6-ray typical urban channel model with the maximum Doppler frequency of 5.55 Hz is assumed. The transmission power of the macrocells and picocells is 46 dBm and 30 dBm, respectively. The antenna gain at the macrocell, picocell, and users are 14 dBi, 5 dBi, and 0 dBi, respectively. Two-antenna transmission and two-antenna diversity reception are assumed. In the evaluation, a full buffer traffic model and reference signal received power (RSRP)-based cell selection with 16 dB offset for picocells is used. The averaging constant ε of PFS is set to 0.001.

We show in TABLE II one snapshot when four users are connected to a picocell with $d(1)=213$, $d(2)=102$, $d(3)=26$, and $d(4)=13$. Then according to (16), $K=3$ because $G(d(4))-1= 4{\cdot}13/(13+1)-1=2.71\leq 3<G(d(3))=4{\cdot}26/(26+1)=3.85$. From $3< G(d(4))=4{\cdot}13/(13+1)=3.71<4$, we have $S_p=\{1,2,3\}$, $S_{np}=\phi$, $S_{pnp}=\{4\}$ according to (20) and (21). Fig. 4(a) and Fig. 4(b) respectively show the assignments, $b_{NR}(l,m,n)$ and $b_{SR}(l,m,n)$, according to the PFS with and without scheduling restriction. When the scheduling restriction is not applied, three out of four users are scheduled on both R_p and R_{np}. In contrast, with restriction, only the user with $n=4$ is scheduled on both resources. The other users scheduled only in R_p show larger quality difference between the two resources.

B. Performance Comparison

Fig. 5 shows the cumulative distribution function (CDF) of the picocell user throughputs. Here, NR (which stands for “no restriction”) represents scheduling results of unrestricted PFS, and SR(x) represents results of PFS under the proposed restriction with $L=x$ (SR stands for “scheduling restriction”). As shown, regardless of scheduling restriction and L, almost identical user throughput performances are obtained, meaning that the performance requirement of Section II.A is satisfied by the proposed restriction scheme. Note the update period of scheduling restriction, L, is set to quite large numbers, making the last two terms of (32) neglible. TABLE III shows the sum throughput and the 5% user throughput of the restricted PFS, both normalized by the respective values of the unrestriced PFS. It can be reconfirmed that the degradation introduced by the scheduling restriction is minimal, which is less than 2%.

TABLE II. Exemplary Picocell

User index		1	2	3	4
Data rate (Mbps)	$r_p(n)$	22.0080	5.2819	5.2819	2.6410
	$r_{np}(n)$	0.1032	0.0516	0.2063	0.2063
$d(n)$		213	102	26	13
Protected		Yes	Yes	Yes	Yes
Non-protected		No	No	No	Yes

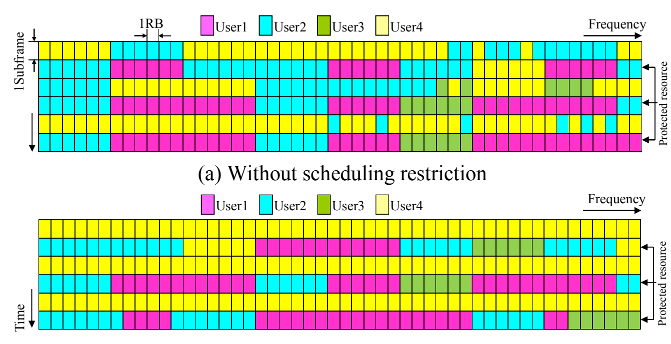

Figure 4. Example of assignments

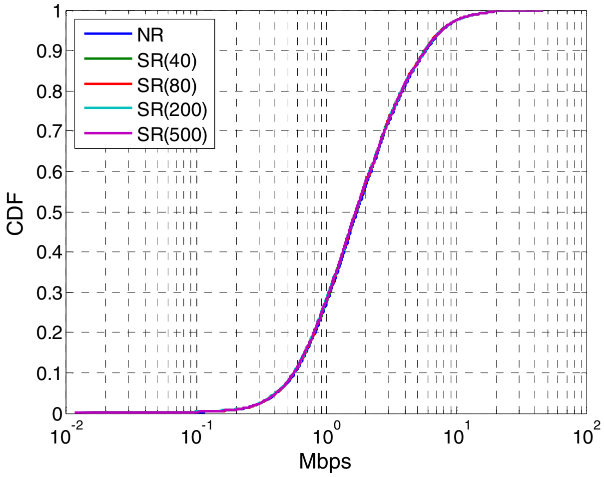

Figure 5. User throughput CDF

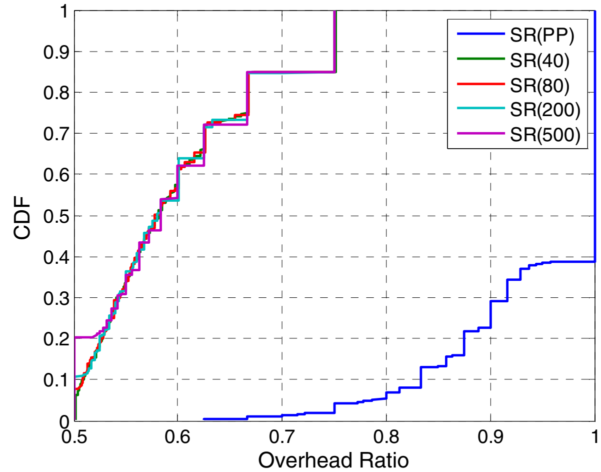

Figure 6. Overhead ratio CDF

C. Feedback Comparison

From (32), the overhead ratio O_{SR}/O_{NR} is dependent on L, M, N, Q and $|S_{pnp}|$. To investigate the feedback reduction benefit of our scheduling restriction scheme under practical settings, we obtained the overhead ratios of each picocell with $N\geq2$, using the values obtained by the simulation. Note picocells with N=1 are excluded because scheduling restriction is not applied to such cells (see Section II.C). Fig. 3 shows the average overhead ratios of the picocells with N=2,3,…,12. As shown, regardless of L, almost identical overhead ratios are obtained. With N=2, the average overhead ratio corresponds to the overhead ratio of a picocell with $|S_{pnp}|$=1, which suggests that most of the picocells with N=2 have a user scheduled both in R_p and R_{np} and the other user scheduled in only one of the two. This results in a relatively large overhead ratio of 0.75 when N=2. The strength of our scheduling restriction scheme, however, is in the overhead reduction for the picocells with large N, where the feedback overhead matters the most. The overhead ratio is 0.58 (i.e. more than 40% reduction) for N=4 and, with increasing N, it converges approximately to 0.50, which corresponds to the feedback overhead for cells with only one resource. Fig. 6 shows the CDF of the overhead ratios. Significant overhead reduction benefit of the proposed restricted scheduling is observed with the average overhead ratio of 0.60, which means 40% overhead reduction on average.

As shown in Fig. 6, we also obtained the overhead ratios of SR(PP) to verify the argument of Section II.C on the inappropriateness of the scheme as scheduling restriction. Although a priori knowledge of $b(l,m,n)$ is not available in practice, it is possible to compute the overhead ratios of SR(PP) by processing the scheduling results of the unrestricted PFS. As stated earlier, the overhead ratios of the scheme are quite large with an average value of 0.95. This confirms the argument of Section II.B.

TABLE III. NORMALIZED USER THROUGHPUT PERFORMANCE (%)

	SR(40)	SR(80)	SR(200)	SR(500)
Sum throughput	98.4	98.6	98.6	98.6
5% user throughput	98.3	98.4	98.8	99.2

V. CONCLUSIONS

We studied a scheduling restriction scheme for interference coordinated heterogeneous networks having two resources with different channel quality statistics. With the proposed, PFRA-based scheduling restriction, the scheduler only needs the detailed channel quality feedback for either protected or non-protected resource for most users, which results in the feedback reduction of a picocell by up to 50%. Simulation results under practical settings show that the performance degradation due to scheduling restriction is less than 2%, and the average feedback reduction is 40%. The proposed scheduling restriction scheme quite nicely makes tradeoff between the performance and the feedback.

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