Adaptive Partial Frequency Reuse in LTE-Advanced Relay Networks

Chen Sun*, Jian Shu*, Wei Zheng*, Zhiyong Yang* and Xiaojun Wang†
*School of Software
Nanchang Hangkong University, Nanchang, Jiangxi, China
†School of Electronic Engineering
Dublin City University, Dublin, Ireland

Abstract—**With the employment of relay nodes (RNs) in Long Term Evolution Advanced (LTE-Advanced) networks, some cell-edge User Equipments (UEs) are served by RNs to improve received signal strength and mitigate interference. In in-band mode, they are allowed to reuse the resources allocated to the UEs connected to the evolved Nodes B (eNBs) in the same cell. Frequency reuse inside a cell can increase the number of available resources per cell and can also produce intra-cell interference. In order to alleviate the detrimental impact of interference and maximise network performance at the same time, we propose an adaptive partial frequency reuse (APFR) scheme, which includes a resource partitioning algorithm and a route selection algorithm. We first formulate the APFR problem into a generalised proportional fairness problem. After getting a mathematical solution, we determine the number of reused resources, and then the resource partitioning and route selection algorithms are derived sequentially. Simulation results show that the proposed APFR scheme can achieved both larger throughput and better fairness than the benchmarking algorithms with different RN transmitting power and various RN positions.**

1. Introduction

In LTE-Advanced standards [1], Orthogonal Frequency Division Multiple Access (OFDMA) is defined as a physical layer technique, and several types of RNs are specified as well. RNs are usually deployed between eNBs and some cell-edge UEs. These UEs are provided a more connection option—accessing the eNBs via RNs, which are called relay UEs. Additionally, two new types of links are created by RNs, access links between the RNs and their associated relay UEs, and back-haul links between the RNs and their home eNBs.

With Type I in-band RNs defined in [1], access links are allowed to reuse the resources occupied by direct links between the eNBs and their UEs. Despite the fact that the overall resource number in a cell grows up, amplifying co-channel interference between access and direct links will diminish the performance gain brought by frequency reuse. In order to simultaneously increase available resource numbers and alleviate the negative effect of intra-cell interference, frequency planing schemes and interference coordination technologies are investigated in many studies.

In single-hop OFDMA networks, partial frequency reuse (PFR) and soft frequency reuse (SFR) are conventional interference coordination techniques. Modified PFR and SFR schemes in two-hop OFDMA networks are proposed in [2], [3], [4], [5]. These papers focus on reducing intra-cell and inter-cell interference by allocating a fixed number of resources to each link. However, when the distribution of UEs in a cell is neither even or constant, these static interference coordination schemes will lead to unbalance between different links.

Load balance is considered in [6], [7], [8], using proportional fair based resource partitioning. Through the formulation of generalised proportional fairness problem, the resource partitioning algorithms under None Frequency Reuse (NFR) and Full Frequency Reuse (FFR) are derived respectively in [6], [7]. In [8], the frequencies used by RNs are different from the eNBs in the same cell as well as the RNs in the neighbouring sectors. Oyman [9] studies centralised resource allocation under the circumstances of NFR and FFR . As two extreme frequency reuse situations, FFR maximises the number of available resources per cell, while NFR eliminates the interference between access links and direct links. Neither of them can guarantee an optimised performance, because they fail to make an effective compromise between increasing resource number and decreasing interference.

Since adaptive partial frequency reuse (APFR) is an intermediate situation between NFR and FFR and may result in better network performance, it has drawn many attentions. The authors in [10] present an APFR scheme, in which direct links can dynamically reuse part of the resources assigned to access links according to whether their outage requirement is satisfied or not. A max-min resource allocation scheme based on APFR is first suggested in [11]. Furthermore, a simplified and effective APFR based resource allocation algorithm for the purpose of maximising the throughput of worst UEs is proposed in [12]. Through adding channel grouping and borrowing to the conventional PFR scheme, a dynamic fractional frequency allocation algorithm is designed in [13]. The authors in [14] group UEs according to their interference ratios and channel conditions and propose a route selection and resource partition strategy

978-1-4673-8590-9/15/$31.00 ©2015 IEEE

in order to improve the performance of the UEs suffering from severe intra-cell interference. [15] suggests using Coordinated Multiple Points (CoMP) in a APFR scheme. In [16], the authors concentrate on interference from neighbouring RNs to the near-RN direct UEs. A radio resource management scheme is proposed in this paper to improve direct UEs and maximise network throughput.

Proportional fairness is a promising trade-off between total throughput and fairness between individual UEs. However, it has not been adequately investigated in the existing literature on the area of APFR. In this paper, we propose a proportional fair based APFR scheme. By formulating the APFR problem in LTE-Advanced relay networks into a generalised proportional fair (GPF) problem and solving it mathematically, a near-optimal number of reused resources can be decided. Then, a resource partitioning and a route selection algorithm are proposed. The empirical results show that our scheme can achieve better performance in both throughput and fairness under different conditions, compared with benchmarking schemes.

The remainder of this paper is organised as follows. Section 2 describes system models in this paper. Section 3 builds the formulation of APFR problem into GPF problem. Section 4 solves the GPF problem and reaches the result as quick as possible by analysing two extreme situations, NFR and FFR. The performance of LTE-Advanced networks with Type I RNs is evaluated in Section 5. Section 6 summarises this paper.

2. System Models

In this paper, the downlink transmission in a LTE-Advanced network with Type I relay nodes is considered. In the cell of interest, an donor eNB is deployed in the centre with three sectors, while single or multiple RNs are located in the edge area of each sector. In this study, the single RN scenario is considered for analysis simplicity, and the analysis can be readily extended to multi-RN scenarios. Randomly distributed UEs $\mathcal{M}$ are either served by the donor eNB directly or connected the RN using two-hop transmission. The UEs served directly by the eNB are direct UEs $\mathcal{M}_d$, and those UEs served by the RN are relay UEs $\mathcal{M}_r$. There are $|\mathcal{M}_d|$ direct UEs and $|\mathcal{M}_r|$ relay UEs. Note that, $|\bullet|$ means the cardinality of a set. The transmission between the eNB and the direct UEs is called direct links, the transmission between the RNs and their associated relay UEs is named as access links, and the transmission between the eNB and the subscribed RNs is expressed as backhaul links.

A LTE-Advanced radio frame is divided into backhaul subframes and access subframes. In the backhaul subframes, the resources are assigned to the backhaul links first, and the rest of resources are allocated to the direct UEs. In the access subframes, part of the resources are reused by the direct links and the access links, and rest of them are only occupied by the direct UEs. Physical Resource Block (PRB) is a fundamental unit of resources. In the reused resources, the average data rate per PRB of direct link in the presence of interference from RNs is denoted as $\bar{E}_{d,m}^{w/i}$. In the non-reused resources, the average data rate per PRB of direct link in the absence of interference from RNs is represented as $\bar{E}_{d,m}^{w/oi}$, and the average data rate per PRB of access link can be expressed as $\bar{E}_{r,m}$. The PRB number in the access subframes is N_a, including the number of reused PRBs denoted as $N^{w/i}$ and the number of non-reused PRBs $N^{w/oi}$. Since the PRB number in the backhaul subframes and the overall PRB number are named as N_b and N respectively, the following can be expressed.

$$N = N_a + N_b = N^{w/i} + N^{w/oi} + N_b \qquad (1)$$

3. Generalised Proportional Fairness (GPF) Problem Formulation

In this paper, how to maximise the proportional fairness with adaptive PFR (PF-APFR) can be formulated as a generalised proportional fair (GPF) problem. The objective of the GPF problem is to maximise the utility of the sum of logarithmic data rates, described as:

$$\begin{aligned} &\max \sum_{m \in \mathcal{M}_d \cup \mathcal{M}_r} \log R_m \\ &= \max\Big(\sum_{m \in \mathcal{M}_d} \log R_{d,m} + \sum_{m \in \mathcal{M}_r} \log R_{r,m}\Big) \end{aligned} \qquad (2)$$

By assuming that a proportional fair (PF) scheduling algorithm is utilised for the direct UEs and the relay UEs, a fixed scheduling gain can be obtained over the Round-Robin , according to the findings in [17]. Therefore, the UE data rates can be simplified into the values related to the resource number and the average spectral efficiency. Considering the reused resources and the non-reused resources occupied by the direct UEs, the data rate of each direct UE can be expressed as:

$$R_{d,m} = \Big(\frac{N^{w/oi}}{|\mathcal{M}_d|}\bar{E}_{d,m}^{w/oi} + \frac{N^{w/i}}{|\mathcal{M}_d|}\bar{E}_{d,m}^{w/i}\Big)G_d(|\mathcal{M}_d|) \qquad (3)$$

where $G_d(|\mathcal{M}_d|)$ indicates the gain of PF scheduling algorithm over Round-Robin scheduling, which is related to the number of the scheduled UEs; $\bar{E}_{d,m}^{w/i}$ and $\bar{E}_{d,m}^{w/oi}$ denote the average data rates per PRB with and without reusing respectively; and $N^{w/i}$ and $N^{w/oi}$ represent the numbers of reused PRBs and non-reused PRBs separately. Since the relay UEs only occupy the reused resources, their data rates can be expressed as:

$$R_{r,m} = \frac{N^{w/i}}{|\mathcal{M}_r|}\bar{E}_{r,m}G_r(|\mathcal{M}_r|) \qquad (4)$$

The data rates of relay UEs should also be transmitted in the backhaul links. Thus, the backhaul PRB numbers used by these relay UEs can be calculated as:

$$\begin{aligned} N_b &= \frac{\sum_{m \in \mathcal{M}_r} R_{r,m}}{E_{r,0}} \\ &= N^{w/i}\frac{\sum_{m \in \mathcal{M}_r} \bar{E}_{r,m}}{|\mathcal{M}_r|E_{r,0}}G_r(|\mathcal{M}_r|) = N^{w/i}\theta \end{aligned} \qquad (5)$$

where $E_{r,0}$ denotes the average data rate per PRB in the backhaul link between the RN r and the donor eNB, and θ represents the backhaul-to-access ratio, which is defined as

$$\theta = \frac{\sum_{m\in\mathcal{M}_r} \bar{E}_{r,m}}{|\mathcal{M}_r| E_{r,0}} G_r(|\mathcal{M}_r|) \tag{6}$$

By substituting (3) and (4) into (2), the GPF maximisation can be rewritten as:

$$\begin{aligned}\max\{&|\mathcal{M}_r|\log N^{w/i} + \sum_{m\in\mathcal{M}_r} \log\frac{G_r(|\mathcal{M}_r|)\bar{E}_{r,m}}{|\mathcal{M}_r|}\\ &+ \sum_{m\in\mathcal{M}_d} \log(N^{w/oi} + N^{w/i}\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}})\\ &+ \sum_{m\in\mathcal{M}_d} \log\frac{G_d(|\mathcal{M}_d|)\bar{E}^{w/oi}_{d,m}}{|\mathcal{M}_d|}\}\end{aligned} \tag{7}$$

After all the UEs have decided their serving nodes, their average data rates per PRB can be measured. Thus, the GPF problem can be transformed into the problem of determining an optimal PRB number for each set of links, which can be also called as a resource partitioning problem. The resource partitioning problem for PF-APFR can be described as

$$\begin{aligned}\max U(N^{w/i}) &= \max\{|\mathcal{M}_r|\log N^{w/i}\\ &+ \sum_{m\in\mathcal{M}_d} \log(N^{w/oi} + N^{w/i}\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}})\}\\ s.t.\ & N^{w/i} + N^{w/oi} + N_b = N\end{aligned} \tag{8}$$

4. Proportional Fair Joint Route Selection and Resource Partitioning Algorithm for APFR

4.1. A Near-Optimal Resource Partitioning Algorithm

Using the expression (5), the resource partitioning problem for PF-APFR (8) can be turned into the utility maximisation related to $N^{w/i}$. We maximize (8) using the method of Lagrange multipliers.

$$\begin{aligned}&L(N^{w/i}, N^{w/oi}, \lambda)\\ =&|\mathcal{M}_r|\log N^{w/i} + \sum_{m\in\mathcal{M}_d} \log(N^{w/oi} + N^{w/i}\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}})\\ &+ \lambda(N^{w/i} + N^{w/oi} + N_b - N)\\ =&|\mathcal{M}_r|\log N^{w/i} + \sum_{m\in\mathcal{M}_d} \log(N^{w/oi} + N^{w/i}\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}})\\ &+ \lambda(N^{w/i} + N^{w/oi} + N^{w/i}\theta - N)\end{aligned} \tag{9}$$

The gradients of the Lagrange function respect to $N^{w/i}$ and $N^{w/oi}$ can be obtained respectively as

$$\begin{aligned}&\frac{\partial L(N^{w/i}, N^{w/oi}, \lambda)}{\partial N^{w/i}} =\\ &\frac{|\mathcal{M}_r|}{N^{w/i}} + \sum_{m\in\mathcal{M}_d} \frac{\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}}}{N^{w/oi} + N^{w/i}\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}}} + \lambda(1+\theta)\end{aligned} \tag{10}$$

$$\begin{aligned}&\frac{\partial L(N^{w/i}, N^{w/oi}, \lambda)}{\partial N^{w/oi}} =\\ &\sum_{m\in\mathcal{M}_d} \frac{1}{N^{w/oi} + N^{w/i}\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}}} + \lambda\end{aligned} \tag{11}$$

By setting the gradients in (10) and (11) equal 0, the following equations can be derived.

$$\begin{aligned}&\frac{|\mathcal{M}_r|}{N^{w/i}} + \sum_{m\in\mathcal{M}_d} \frac{\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}}}{N^{w/oi} + N^{w/i}\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}}}\\ =&(1+\theta)\sum_{m\in\mathcal{M}_d} \frac{1}{N^{w/oi} + N^{w/i}\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}}}\end{aligned} \tag{12}$$

$$|\mathcal{M}_r| = \sum_{m\in\mathcal{M}_d} \frac{1+\theta-\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}}}{\frac{N^{w/oi}}{N^{w/i}} + \frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}}} \tag{13}$$

The value range of $\frac{N^{w/oi}}{N^{w/i}}$ is between 0 and positive infinite, and the value of $\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}}$ is between 0 and 1. It can be proven that in the case that the number of direct UEs is larger than the relay UE number, there is always a value of $\frac{N^{w/oi}}{N^{w/i}}$ to satisfy the equation (13). Hereafter, a near-optimal resource partitioning, $N^{w/i}$, N_b and N_a, can be obtained.

For different direct UEs, $\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}}$ has different values, reflecting different degrees of the effects of interference. It can be readily observed that the optimal value of $\frac{N^{w/oi}}{N^{w/i}}$ cannot be directly calculated through equation (13). Besides, it can also be seen that with larger $\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}}$, the right side of equation (13) becomes smaller, and the ratio $\frac{N^{w/oi}}{N^{w/i}}$ should be smaller to hold the balance of the equation.

In general, the distribution of $\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}}$ cannot be estimated. By intentionally designing $\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}}$, no frequency reuse (NFR) and full frequency reuse (FFR) can be generated as two special situations of APFR.

No frequency reuse. the NFR situation indicates a situation that all the direct UEs have $\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}} = 0$. It always implies the case that PRBs in the access subframes are no more reused by the direct links and the access links, but shared orthogonally.

The resource partitioning of NFR has been discussed in [18]. Through equation (13), $\frac{N^{w/oi}}{N^{w/i}}$ can be derived as

$$\frac{N^{w/oi}}{N^{w/i}} = (1+\theta)\frac{|\mathcal{M}_d|}{|\mathcal{M}_r|} \tag{14}$$

After several steps of calculation, the optimal resource partitioning can be obtained as

$$N^{w/i} = \frac{1}{1+\theta}\frac{|\mathcal{M}_r|}{|\mathcal{M}|}N \tag{15}$$

$$N_b = \frac{\theta}{1+\theta}\frac{|\mathcal{M}_r|}{|\mathcal{M}|}N \tag{16}$$

$$N^{w/oi} = \frac{|\mathcal{M}_d|}{|\mathcal{M}|}N \tag{17}$$

where $N^{w/oi}$ represents the PRB number occupied only by the direct UEs, and $N^{w/i}$ is the the PRB number occupied only by the relay UEs in the access links.

Full frequency reuse. the FFR situation denotes a situation that all the PRBs in the access subframes are reused by the direct links and the access links. However, the throughput balance between access link and backhaul link is not considered. It also suggests a case that all the direct UEs are not impacted by the interference from the relay UEs in different PRBs. In both situations, $\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}} = 1$ for every direct UEs.

The resource partitioning in this situation has been discussed in [7]. Through equation (13), $\frac{N^{w/oi}}{N^{w/i}}$ can be derived as

$$\frac{N^{w/oi}}{N^{w/i}} = \theta\frac{|\mathcal{M}_d|}{|\mathcal{M}_r|} - 1 \tag{18}$$

After several steps of calculation, the optimal resource partitioning can be obtained as

$$N^{w/i} = \frac{1}{\theta}\frac{|\mathcal{M}_r|}{|\mathcal{M}|}N \tag{19}$$

$$N_b = \frac{|\mathcal{M}_r|}{|\mathcal{M}|}N \tag{20}$$

$$N_a = \frac{|\mathcal{M}_d|}{|\mathcal{M}|}N \tag{21}$$

where N_a represents the number of PRBs occupied by the direct UEs, and $N^{w/i}$ is the the number of PRBs occupied by the relay UEs in the access links.

Since N_a should be no less than $N^{w/i}$, the following inequality can be given.

$$|\mathcal{M}_d| \geq \frac{|\mathcal{M}_r|}{\theta} \tag{22}$$

Proposed Algorithm. In the FFR situation, the largest values of $\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}}$ are considered for all direct UEs. Thus, the largest ratio of $\frac{N^{w/oi}}{N^{w/i}}$ can be obtained. Using this initial ratio, a resource partitioning algorithm for PF-APFR is proposed to decide the integrated values of $N^{w/i}$, N_b and N_a. A near-optimal value of $\frac{N^{w/oi}}{N^{w/i}}$ satisfying equation (13) will also be achieved.

Algorithm 1 A resource partitioning algorithm for PF-APFR

Input: $|\mathcal{M}_r|$, $|\mathcal{M}_d|$: the numbers of relay UEs and direct UEs; θ : the backhaul-to-access ratio; $\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}}$: the ratio of the data rate per non-reused PRB to the data rate per reused PRB of each direct UE $\forall m \in \mathcal{M}_d$

Output: $N^{w/i}$, N_b and N_a

Initialise $N^{w/i} = \lceil \frac{1}{\theta}\frac{|\mathcal{M}_r|}{|\mathcal{M}|}N \rceil$

repeat

  $N^{w/i} = N^{w/i} - 1$;

  Calculate $N_a = \lceil N - \theta N^{w/i} \rceil$;

  Calculate $N^{w/oi} = N_a - N^{w/i}$;

  for all $m \in \mathcal{M}_d$ **do**

    Calculate $temp1 = \sum_{m \in \mathcal{M}_d} \frac{1+\theta-\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}}}{\frac{N^{w/oi}}{N^{w/i}} + \frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}}}$;

  end for

until $temp1 \leq |\mathcal{M}_r|$, or $N^{w/i} \leq \frac{1}{1+\theta}\frac{|\mathcal{M}_r|}{|\mathcal{M}|}N$

return $N^{w/i}$; $N_a = \lceil N - \theta N^{w/i} \rceil$; $N_b = N - N_a$

Complexity analysis. The complexity of this algorithm is based on the number of possible integrated values of $N^{w/i}$. Ranging from $\frac{1}{1+\theta}\frac{|\mathcal{M}_r|}{|\mathcal{M}|}N$ to $\frac{1}{\theta}\frac{|\mathcal{M}_r|}{|\mathcal{M}|}N$, there are $\frac{1}{\theta+\theta^2}\frac{|\mathcal{M}_r|}{|\mathcal{M}|}N$ possible integrated values for $N^{w/i}$. As the calculation of $temp1$ needs $|\mathcal{M}_d|$ times of basic operations, the complexity of this algorithm is $\mathcal{O}(\frac{|\mathcal{M}_d|}{\theta^2}\frac{|\mathcal{M}_r|}{|\mathcal{M}|}N)$.

4.2. A Route Selection Algorithm for PF-APFR

According to what is shown in equation (13), the resource partitioning for PF-APFR is related to the numbers of UEs, e.g., $|\mathcal{M}_d|$ and $|\mathcal{M}_r|$, and the spectral efficiency of direct UE $E_{d,m}$, which are decided by route selection. Therefore, joint processing of route selection and resource partitioning can improve the proportional fairness further.

Assuming that new coming UEs arrive in a one-by-one manner. Firstly, for each new UE m, a sector with an eNB and a RN is selected according to received signal power. There are two routes to be further chosen, either direct route to the eNB or relay route via the RN to the eNB. Secondly, the resource partitioning results of choosing these two routes can be calculated through the proposed resource partitioning algorithms. By substituting the resource partitioning results into equation (8), the possible utility of choosing both routes can be obtained. Finally, after the comparison between these two candidate routes, the route with larger possible utility is selected. The detail of the route selection algorithm for PF-APFR is described below

Algorithm 2 A route selection algorithm for PF-APFR

Input: $P_{m,k}, \forall m \in \mathcal{M}, \forall k \in \mathcal{K}$: the received signal power of UE m in $\mathcal{M}$ from sector k in $\mathcal{K}$; $|\mathcal{M}_r|$, $|\mathcal{M}_d|$: the current numbers of relay UEs and direct UEs; θ : the backhaul-to-access ratio; $\frac{\bar{E}^{w/i}_{d,m}}{\bar{E}^{w/oi}_{d,m}}$: the ratio of the data rate per non-reused PRB to the data rate per reused PRB of each direct UE $\forall m \in \mathcal{M}_d$

Output: k : the selected sector; s : the selected route, either the eNB d or the RN r

For a new arriving UE m,
$k = \arg\max_{\mathcal{K}} P_{m,k}$;
Update $\mathcal{M}_r = \{\mathcal{M}_r, m\}$;
Calculate $N^{w/i}$, N_a and N_b using Algorithm 1;
Calculate U_r using (8);
Update $\mathcal{M}_d = \{\mathcal{M}_d, m\}$;
Calculate $N^{w/i}$, N_a and N_b using Algorithm 1;
Calculate U_d using (8);
$s = \arg\max(U_r, U_d)$;
return k; s.

Complexity analysis. The complexity of the proposed route selection algorithm is the number of UEs times the sum of the number of sectors plus the complexity of the proposed resource partitioning algorithm, which can be depicted as $\mathcal{O}(|\mathcal{M}| \times (|\mathcal{K}| + \frac{|\mathcal{M}_d|}{\theta^2}\frac{|\mathcal{M}_r|}{|\mathcal{M}|}N))$.

5. Performance Evaluation

5.1. Simulation Parameters

According to LTE self-evaluation methodology [19], a semi-static system-level simulation platform is developed on a personal computer to evaluate downlink performance. This simulation platform is based on Matlab, which is widely used in modelling communications systems. With developing computing programs, channel conditions and resource utilisation can be simulated.

Using the wrap-around technique, seven 3-sectored macro cells are generated with a fixed numbers of UEs randomly dropped in them. In each cell, a fixed number of RNs are located at the cell edge with the same distance of half of the inter-site distance from the eNB. The details of the simulation parameters are listed in Table 1.

In this simulation, the network topology considers single-RN scenarios, which is illustrated in Fig. 1. In each sector, there is one RN located at the bore sight towards the adjacent eNB. The Inter-Site Distance (ISD) between two adjacent eNBs is 500 meters. The RN Distance (RND) from the central eNB in the same sector is the ISD multiplied by a variable factor. Different RNDs may impact the performance

TABLE 1. SIMULATION PARAMETERS

Parameters	Values
Carrier/Bandwidth	2GHz /FDD 10MHz
Subframe number	10/radio frame
PRB number	50/subframe
UE number	30/sector
Inter-site distance	500 m
Transmitting power	eNB: 46 dBm RN: 30 dBm
Antenna configuration	eNB: 14 dBi, 70 directional RN: 5 dBi, omni UE: 0 dBi, omni
Thermal noise density	-174 dBm/Hz
Noise figure	9 dB at UE, 5 dB at RN
Channel model	3GPP case 1 for relay [19]
Shadowing standard deviations	Log-normal distribution eNB-RN: 6 dB eNB-UE: 8 dB RN-UE: 10 dB
Fast fading model	SUI-5 channel [20]
Traffic model	Full buffer
AMC scheme	15 levels according to [21]

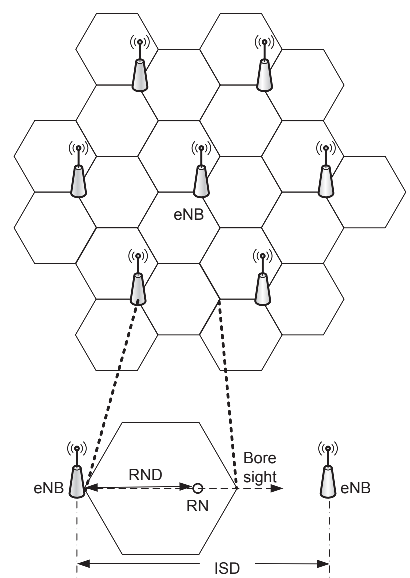

Figure 1. Cellular network layout with one RN

comparison. In addition, the performance with different transmitting power of RN will be evaluated as well.

The joint route selection and resource partitioning algorithm proposed in this paper is based on the analysis of APFR, called "APFR based alg." in the simulation results. Chosen as the benchmarking scheme, the route selection and resource partitioning scheme given in [7] is based on the scenario of Full Frequency Reuse (FFR), called "FFR based alg.". In addition, the simulation results of the LTE-Advanced networks without relay are also shown.

In this simulation, the downlink performance of all the UEs in the macro cell is evaluated. The performance of the relay UEs attached to the RNs are also assessed. Macro UEs are defined as the UEs in the macro cell, including the direct UEs and the relay UEs in the same macro cell. The metrics of the evaluation include the GPF factor, the average UE throughput and Jain's fairness [22]. Besides the GPF factor is required to show the effectiveness of the solutions to the GPF problem in equation (2), it is a commonly used metric [17] to show the trade-off between average throughput and fairness, which is expressed as:

$$GPF\ factor = \frac{1}{|\mathcal{M}|} \sum_{m \in \mathcal{M}} \log R_m \tag{23}$$

Jain's fairness index proposed in [22] is also a quantitative measure of fairness for resource allocation, which can identify the proportion of under-allocation. Jain's fairness of n users with x_i throughput is described as:

$$\mathcal{J}(x_1, x_2, \ldots, x_n) = \frac{(\sum_{i=1}^{n} x_i)^2}{n \cdot \sum_{i=1}^{n} x_i^2} \tag{24}$$

5.2. Simulation Results

The performance using the proposed Joint Route Selection and Resource Partitioning (JRSRP) algorithm based on APFR and the benchmarking JRSRP algorithm based on FFR is evaluated when different values are given to the transmitting power of RN . The RN transmitting power of 30 dBm, 33 dBm, 36 dBm and 39 dBm are used in the simulation.

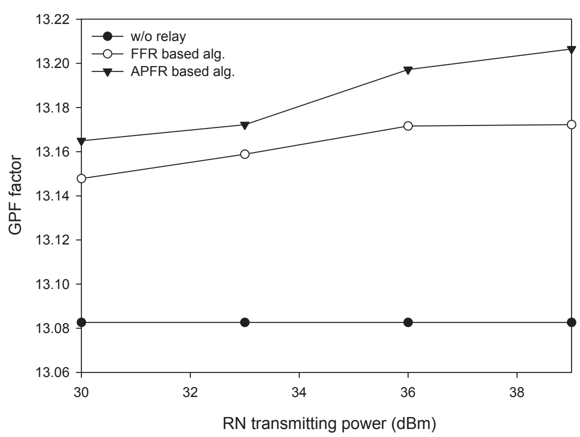

Figure 2. GPF factor v.s. RN transmitting power

Fig.2 shows the GPF factors using different JRSRP algorithms with different RN transmitting power. With two-hop relaying, the GPF factors using both the proposed APFR based JRSRP algorithm and the FFR based algorithm are larger than those in the LTE-Advanced networks without relay. With the increase of transmitting power of RNs, better downlink performance of access links can be achieved, but more severe interference will be generated to the direct links. Because of better dealing with this situation, the APFR based algorithm improves the GPF factors in different RN transmitting power, compared with the FFR based algorithm.

It can be observed that the GPF factors using the FFR based JRSRP algorithm are increasing gently, especially when the RN transmitting power grows from 36 dBm to 39 dBm. However, the increment of GPF factor using the APFR based algorithm is more significant between these two RN transmitting power. Therefore, the APFR based algorithm may support larger transmitting power of RNs in the LTE-Advanced networks in order to provide better proportional fairness.

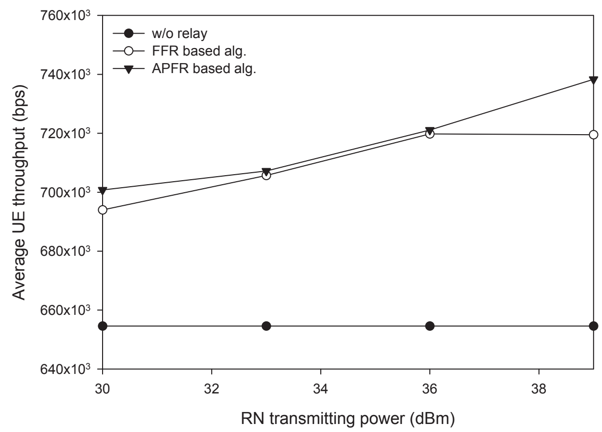

Figure 3. Average UE throughput v.s. RN transmitting power

The average throughputs of UEs using different JRSRP algorithms versus different RN transmitting power are displayed in Fig. 3. Deploying RNs, larger throughputs are obtained, compared with the LTE-Advanced networks without relay node. Similar with what is shown in Fig. 2, the average throughputs using the FFR based algorithm increase insignificantly along with the arising of RN transmitting power, and those using the APFR based algorithm are increasing gradually. When the transmitting power of RNs reaches 39 dBm, the gap of average throughputs using the two JRSRP algorithms is much larger than those in other RN transmitting power.

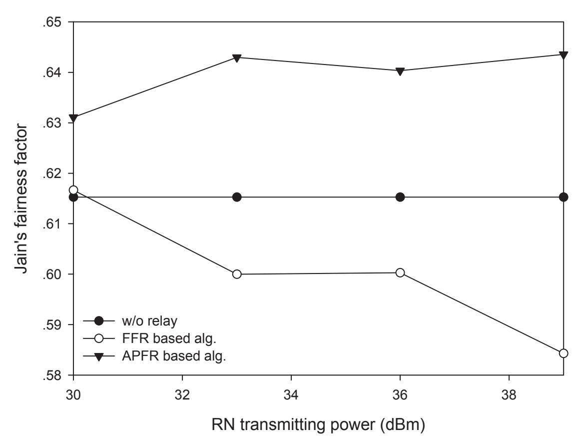

Figure 4. Jain's fairness index v.s. RN transmitting power

In Fig. 4, the Jain's fairness factors verses the RN transmitting power using different JRSRP algorithms are presented. Along with the increasing RN transmitting power, the Jain's fairness factors show two different trends using the APFR based algorithm and the FFR based algorithm. The Jain's fairness factors fall significantly using the FFR based algorithm and increase slightly using the APFR based algorithm. The higher transmitting power the RNs have, the more improvement in terms of Jain's fairness factor can be obtained by the APFR based algorithm. Additionally, the FFR based algorithm will achieve lower Jain's fairness factors than those in the LTE-Advanced networks without relay, when the RN transmitting power is no less than 33 dBm. Therefore, high transmitting power of RN is not recommended, unless the proposed APFR based JRSRP algorithm is applied.

Besides the transmitting power, the position of RNs may also affect the performance of LTE-Advanced networks with relay. When a RN is located closer to the eNB, the channel condition of its access links will get worst because of increasing interference from the direct links, but the backhaul link condition will be better thanks to shorter path between the RN and the eNB. Note that the position of RN is at the bore sight towards the adjacent eNB and the distance between the eNBs and their RNs is 0.3, 0.35, 0.4, 0.45 and 0.5 of the distance between two adjacent eNBs, i.e. inter-site distance (ISD).

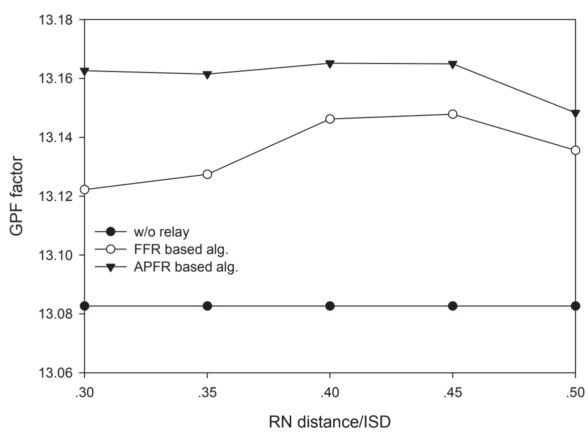

Figure 5. GPF factor v.s. RN position

In Fig. 5, the GPF factors with different RN positions are shown. When the RNs move outside from 0.3 of the ISD to 0.5 of the ISD, both the proposed JRSRP algorithm based on APFR and the benchmark algorithm based on FFR can obtain the GPF factor gains, and the proposed APFR based algorithm can always achieve better GPF factors than the benchmarking FFR based algorithm. When the RNs is getting closer to the eNBs, downlink performance of access links is getting worse, while backhaul link performance is getting better. It can be observed that the GPF factors using the FFR based JRSRP algorithm are decreasing gradually, when the RNs moves towards their donor eNBs from 225 meters (0.45 of the ISD) away from them to 150 meters (0.3 of the ISD). However, the GPF factors using the APFR based algorithm have insignificant differences except when the distance of RN is half of the ISD. Therefore, the APFR based algorithm allows closer RN locations in the LTE-Advanced networks.

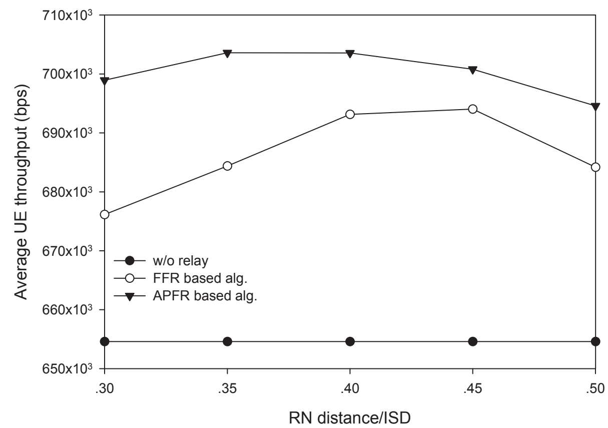

Figure 6. Average UE throughput v.s. RN position

The average throughputs of UEs using different JRSRP algorithms versus different RN distances are displayed in Fig. 6. Deploying RNs, larger throughputs are obtained, compared with the LTE-Advanced networks without relay node. Similar with what is shown in Fig. 5, the average throughput using the FFR based algorithm increases gradually along with larger RN distance away from the eNB before the RN distance reaches 0.35 of the ISD. Besides, the average UE throughput using the APFR based algorithm reaches the peak when the RNs are located at 0.35 of the ISD away from their eNBs. The difference of the average UE throughput using these two algorithms is the largest when the distance between the RNs and their eNBs is only 150 meters (0.3 of the ISD), and the smallest when the RN distance is 0.45 of the ISD.

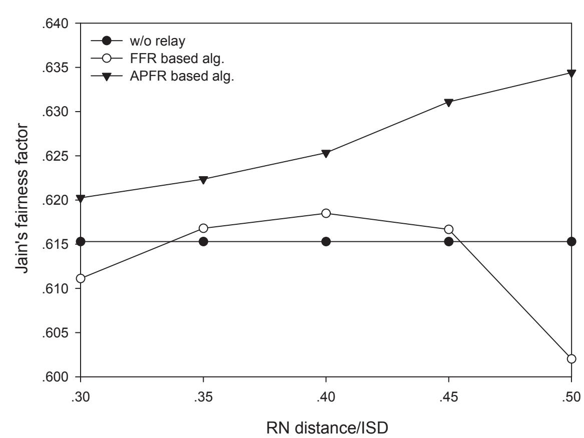

Figure 7. Jain's fairness index v.s. RN position

In Fig. 7, the Jain's fairness factors verses the RN distance to the ISD using different JRSRP algorithms are depicted. At different locations of RN, the Jain's fairness factors show two different trends using the APFR based algorithm and the FFR based algorithm respectively. The Jain's fairness factors using the FFR based algorithm increase steadily with the RN distance of from 0.3 of the ISD to 0.4 of the ISD, and then fall below the value without relay with the largest RN distance. On the contrary, the jain's fairness factors using the APFR based algorithm increase gradually along with further RN distance. This is because when the RNs are further away from their eNB, more cell-edge UEs can choose the RNs in order to improve their performance. Hence, the difference between cell-center UEs and cell-edge UEs will be narrowed and better fairness will be achieved.

6. Conclusion

This paper investigates adaptive partial frequency reuse (APFR) problem in LTE-Advanced relay networks. In order to deal with this problem, we proposed a joint resource partitioning and route selection algorithm to achieve better proportional fairness. Experimental evaluation proved that the proposed proportional fair based APFR scheme can obtain better average throughput and Jain's fairness factor when different RN transmitting power and RN positions are assumed.

Acknowledgments

This study is supported by Natural Science Foundation of Jiangxi Province (No. 20142BAB217017), Natural Science Foundation of China (No. 61363015 and No. 61262020) and Science and Technology Landing Program for Higher Education of Jiangxi Province (No. KJLD14054).

References

[1] 3GPP, *Requirements for further advancements for E-UTRA (LTE-Advanced)*, 3rd Generation Partnership Project (3GPP) TR 36.913, Jun. 2008. [Online]. Available: http://www.3gpp.org/ftp/Specs/html-info/36913.htm

[2] M. Liang, F. Liu, Z. Chen, Y. F. Wang, and D. C. Yang, "A novel frequency reuse scheme for ofdma based relay enhanced cellular networks," in *Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th*, April 2009, pp. 1–5.

[3] W. Lee, M.-V. Nguyen, J. Jeong, B. Keum, and H. S. Lee, "An orthogonal resource allocation algorithm to improve the performance of ofdma-based cellular wireless systems using relays," in *Consumer Communications and Networking Conference, 2008. CCNC 2008. 5th IEEE*, Jan 2008, pp. 917–921.

[4] M. Reddy, E. Vivier, and F. Kaddour, "Joint benefits of fractional frequency reuse and relays in lte networks," in *Online Conference on Green Communications (GreenCom), 2013 IEEE*, Oct 2013, pp. 127–131.

[5] M. Eguizabal and A. Hernandez, "Sfr-based vs. ffr-based inter-cell interference coordination for inband relay lte-a networks," in *Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), 2014 6th International Congress on*, Oct 2014, pp. 41–47.

[6] Z. Ma, W. Xiang, H. Long, and W. Wang, "Proportional fair resource partition for LTE-Advanced networks with Type I relay nodes," in *Communications (ICC), 2011 IEEE International Conference on*, 2011, pp. 1–5.

[7] J. Wang, Z. Ma, Z. Lv, Y. Sheng, and W. Xiang, "Fairness-aware resource partition and routing in relay-enhanced orthogonal-frequency-divisionmultiple-accessing cellular networks," *Communications, IET*, vol. 6, no. 16, pp. 2613–2620, 2012, iD: 1.

[8] J. Wang, J. Liu, D. Wang, J. Pang, G. Shen, and J. Chen, "Load balance based dynamic inter-cell interference coordination for relay enhanced cellular network," in *Vehicular Technology Conference (VTC Spring), 2012 IEEE 75th*, May 2012, pp. 1–5.

[9] O. Oyman, "Opportunistic scheduling and spectrum reuse in relay-based cellular networks," *Wireless Communications, IEEE Transactions on*, vol. 9, no. 3, pp. 1074–1085, 2010.

[10] Y. Zhao, X. Fang, R. Huang, and Y. Fang, "Joint interference coordination and load balancing for ofdma multihop cellular networks," *Mobile Computing, IEEE Transactions on*, vol. 13, no. 1, pp. 89–101, Jan 2014.

[11] Y. Kim and M. Sichitiu, "Optimal max-min fair resource allocation in multihop relay-enhanced wimax networks," *Vehicular Technology, IEEE Transactions on*, vol. 60, no. 8, pp. 3907–3918, 2011.

[12] Z. Zhao, J. Wang, S. Redana, and B. Raaf, "Downlink resource allocation for lte-advanced networks with type1 relay nodes," in *Vehicular Technology Conference (VTC Fall), 2012 IEEE*, 2012, pp. 1–5.

[13] H. Mei, J. Bigham, P. Jiang, and E. Bodanese, "Distributed dynamic frequency allocation in fractional frequency reused relay based cellular networks," *Communications, IEEE Transactions on*, vol. 61, no. 4, pp. 1327–1336, April 2013.

[14] Y. Pei, H. Tian, T. Wu, and Y. Wang, "Frequency planning scheme based on interference coordination for ofdm-relay systems," *Communications Letters, IEEE*, vol. 15, no. 1, pp. 13–15, January 2011.

[15] Q. Li, R. Hu, Y. Qian, and G. Wu, "Intracell cooperation and resource allocation in a heterogeneous network with relays," *Vehicular Technology, IEEE Transactions on*, vol. 62, no. 4, pp. 1770–1784, 2013.

[16] B.-G. Choi, I. Doh, and M. Y. Chung, "Radio resource management scheme for relieving interference to mues in relay-based cellular networks," *Vehicular Technology, IEEE Transactions on*, vol. 64, no. 7, pp. 3018–3029, July 2015.

[17] S. Borst, "User-level performance of channel-aware scheduling algorithms in wireless data networks," *Networking, IEEE/ACM Transactions on*, vol. 13, no. 3, pp. 636–647, 2005.

[18] Z. Ma, W. Xiang, H. Long, and W. Wang, "Proportional fair-based in-cell routing for relay-enhanced cellular networks," in *Wireless Communications and Networking Conference (WCNC), 2011 IEEE*, 2011, pp. 381–385.

[19] 3GPP, *Evolved Universal Terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA physical layer aspects*, 3GPP TR 36.814. [Online]. Available: http://www.3gpp.org/ftp/Specs/html-info/36814.htm

[20] V. Erceg, K. S. Hari, and M. Smith, "Channel models for fixed wireless applications," IEEE 802.16.3c-01/29r4, Tech. Rep., 2001.

[21] J. Ikuno, M. Wrulich, and M. Rupp, "System level simulation of lte networks," in *Vehicular Technology Conference (VTC 2010-Spring), 2010 IEEE 71st*, 2010, pp. 1–5.

[22] R. Jain, D.-M. Chiu, and W. R. Hawe, *A quantitative measure of fairness and discrimination for resource allocation in shared computer system.* Eastern Research Laboratory, Digital Equipment Corporation, 1984.