PROCEEDINGS OF SCIENCE

A Proportional Fair Resource Allocation Algorithm for Hybrid Hierarchical Backhaul Networks

Xiaocan Lian
Institute of Communication and Information Systems, Hohai University, Nanjing, 211100, China
E-mail: 498807912@qq.com

Guoping Tan[1 2 3]
Institute of Communication and Information Systems, Hohai University, Nanjing, 211100, China
E-mail: gptan@hhu.edu.cn

Yandan Zhu
Institute of Communication and Information Systems, Hohai University, Nanjing, 211100, China
E-mail: yandanzhu_zyd@163.com

Guomin Wu, Yueheng Li
Institute of Communication and Information Systems, Hohai University, Nanjing, 211100, China
E-mail: guomin.wu@wico.sh; yueheng_li@hhu.edu.cn

In order to improve the total system throughput by analyzing the resource allocation problems in backhaul links and access links of base stations in ultra-dense network (UDN), a proportional fair resource allocation (PFRA) algorithm was designed for the wireless hybrid hierarchical backhaul network in this paper. First, the base stations were stratified and the frame structure of each base station in different layeies was re-designed.Then, the objective function was constructed based on the proportional fair utility function to optimize the system throughput. Finally, an iterative algorithm was derived based on Lagrange Multiplier algorithm to obtain the optimal solution of spectrum resource allocation in hybrid hierarchical backhaul network. The performance of the PFRA algorithm has been simulated and the results show that the PFRA algorithm can improve network throughput effectively at the cost of losing a certain network coverage rate. In the future, PFRA needs to be optimized to reach the best balance between network throughput and network coverage rate.

CENet2017
22-23 July 2017
Shanghai, China

[1]Speaker
[2]Corresponding Author
[3]This work was supported by Fundamental Research Funds for the Central Universities (2015B18914; 2014B33114), Key Laboratory of Wireless Sensor Network and Communication, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences (2016001) and Graduate student scientific research innovation projects in jiangsu province (KYLX_0436).

1. Introduction

Complex networks have been widely studied in recent years and different interconnected network models are proposed to solve the cascading failures caused by overload [1-4]. As a new heterogeneous network architecture, ultra-dense network (UDN) is different from the deployment scenario of traditional macro-cell. UDN provides a efficient energy-saving solution to the wireless mobile data services that grow rapidly in the future [5]. Under this network architecture, the number of small-cell base stations (SBSs) is increased and the coverage area of single cell is reduced with denser deployment. Therefore, the load of macro-cell base stations (MBSs) can be shared, the physical distance between the sender and the receiver shortened and low latency and reliable user experience achieved. Meanwhile, UDN reduces the installation cost of the network infrastructure deployment and the operating cost of the base stations significantly [6]. However, the complexity of the network structure makes inter-cell interference more serious. Besides, the spectrum resource and backhaul network capacity is constrained [7]. How to allocate the spectral resource in backhaul and access links of base stations effectively is an important problem in UDN.

How to allocate resource to reach the most total network throughput and spectral highest efficiency will be studied in this paper. Thus, a proportional fair resource allocation (PFRA) algorithm is designed. The objective function to maximize the network throughput in hybrid hierarchical backhaul network is constructed. And an iterative algorithm is derived based on Lagrange Multiplier algorithm to obtain the optimal allocation of spectrum resource. In addition, PFRA algorithm is compared with traditional static allocation algorithms and simulated by MATLAB software respectively. The performances in interms of total network throughput and edge user throughput are compared and the experimental results are analysed.

2. System Model

Hybrid hierarchical backhaul network is a new network structure as proposed in UDN. In actual deployment, the base stations in the next layer only need to establish a backhaul link with the base station in the upper layer to achieve plug and play. In order to simplify and keep general nature, three-hop hybrid hierarchical backhaul network scenario is used in this paper, as shown in Figure 1. MBSs in the first-level backhaul layer (the following is called first layer) is denoted by SN_0 and SBSs in the second-level backhaul layer (the following is called second layer) is denoted by SN_s ($s \in S, s \neq 0$). S is the set of base stations in the first and second layer. SBSs in the third-level backhaul layer (the following is called third layer) is denoted by SN_{sc} ($s \in S, c \in C$). C is the set of base stations in the third layer. The set of User Equipment (UE) is denoted by U. The set of UE connected to the base stations in the first and the second layer is U_s, in the third layer is U_{sc}.

UE is connected to one base station at most at some point to communicate without considering the cooperative transmission. Since only downlink transmission is considered in this paper, the data packets that SBSs transmit to UE are generally sent by MBSs to SBSs. During this period, the data packets transmitted from the upper layer are decoded by SBSs, and queued in the buffer of SBSs, waiting for the scheduler to be transmitted to the corresponding target UE in turn. According to the definition of frame structure in 3GPP LTE [8], the reception and transmission of SBSs can't be carried out at the same time so as to avoid the signal interference.

Therefore, a radio frame is divided into the access subframe and the backhaul subframe. The MBSs and SBSs in each layer simultaneously multiplex the subframe frequency band and transmit data to their own UE at the same time in the access subframe. The MBSs orthogonally allocates frequency band to UE for backhaul link in backhaul subframe. The subframe allocation changes upon the scene, the UE's need or higher configuration.

A basic OFDMA resource allocation unit can be named as a resource block (RB), which is composed of resource elements in column [9]. RB is used as the smallest indepedant resource allocation unit in this paper.

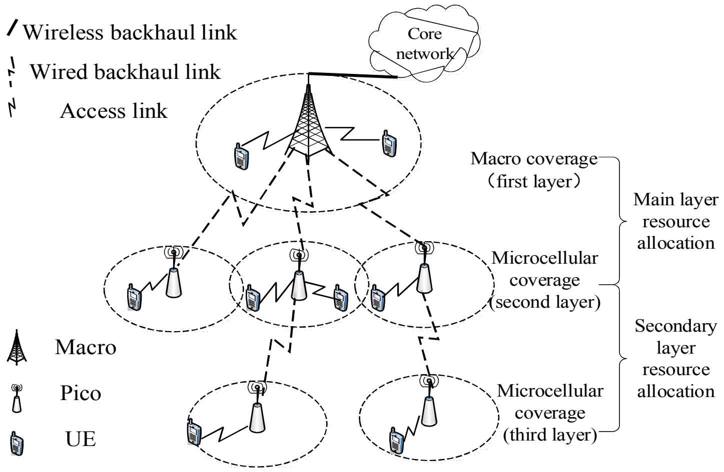


Figure 1: Hybrid Hierarchical Network Framework

3. Proportional Fair Resource Allocation Algorithm

The PFRA algorithm re-designs the frame structure of base stations in different layers based on hybrid hierarchical network framework. The frame structure of SBSs in the second layer is the same as MBSs and opposite to SBSs in the third layer. How many RBs are allocated to each base station is derived from the following algorithm.

The algorithm takes a utility function based on proportional fairness [10]:

$$max \sum_{u\in U} \log R_{u,s} = max \sum_{u\in U} \sum_{s\in S} \rho_{u,s} \log\left(\sum_{j\in J} w_{j,u} r_{j,u}\right) \tag{3.1}$$

$R_{u,s}$ is the received data rate of a UE (denoted by u) which connected to the SN_s on a radio frame. If u is directly connected to the SN_s, $\rho_{u,s}$=1, otherwise $\rho_{u,s}$=0. $w_{j,u}$=1 means that the jth RB is assigned to u, otherwise $w_{j,u}$=0. The $r_{j,u}$ refers to the instantaneous data rate received by u at the jth RB. J is the sum of RBs in a radio frame. (3.1) meet following conditions:

$$\begin{gathered} \sum_{s\in S} \rho_{u,s} = 1, \rho_{u,s} \in \{0,1\}, \forall u \in U \\ \sum_{u\in U} w \le 1, w \in \{0,1\}, \forall j \in J, \forall s \in S \end{gathered} \tag{3.2}$$

3.1 Main Layer Resource Allocation

The main layer resource allocation is that the MBSs allocate the RBs to their own UE and the SBSs in the second layer. Only the access resource of the MBSs and the access and backhaul resource of the SBSs in the second layer are considered. We assume that the data services and service queues of the UE under the MBSs are of full buffer. Therefore, UE belonging to the MBSs can consume all the allocated access resource J_a. The average data rate of u connected to SN_0 is

PoS(CENet2017)036

$$\bar{R}_{u,0} \approx \frac{\lfloor J_a \rfloor}{U_0} f(\bar{\gamma}_{u,0}) G(U_0) \tag{3.3}$$

The scheduling gain $G(U_0)$ =1 due to the Round-Robin (RR) scheduling scheme used. The key idea of the RR scheduling is that the UEs in the cell have the same priority, and each UE is periodically scheduled with equal opportunity. $f(\bar{\gamma}_{u,0})$ denotes the linear mapping function of signal to interference plus noise ratio (SINR) in the access link that from u to SN_0, calculated by

$$f(\bar{\gamma}_{u,0}) = \log_2\left(1 + \frac{R}{N_0 + I}\right) \tag{3.4}$$

R refers to the signal UE received. N_0 is the Gaussian white noise. I means the interference UE received which is an accumulated value. And the SBSs in the second layer not only provide access services to their own UE, but also provide backhaul services to the SBSs in the third layer.

As demostrated below, the average data rate of the u connected to SN_s ($s \in S$, $s \neq 0$) is

$$\bar{R}_{u,s} \approx \frac{\lfloor J_a^s \rfloor}{|U_s + U_s'|} f'(\bar{\gamma}_{u,s}) \tag{3.5}$$

The SBSs in the second layer can't use J_a fully unless the link from SN_0 to SN_s can provide enough transfer rate. Therefore, the access resource J_a^s that SBSs allocated is a part of J_a. U'_s represents the set of UE connected to SBSs in the third layer, $U_s' = \sum_{s \in S} U_{sc}$. If $u \in U_s$, $f'(\bar{\gamma}_{u,s})$= $f(\bar{\gamma}_{u,s})$. If $u \in U'_s$, $f'(\bar{\gamma}_{u,s})$=$f(\bar{\phi}_{sc})$. $f(\bar{\phi}_{sc})$ is the linear mapping function of the SINR in the backhaul link that goes from SN_{sc} to SN_s, calculated as (3.4).

Therefore, the cumulative average data rate $\bar{R}_a^s$ obtained on the allocated access subframe of SN_s is calculated by $\bar{R}_a^s = \sum_{u \in (U_s + U_s')} \bar{R}_{u,s}$. Correspondingly, the cumulative average data rate $\bar{R}_b^s$ obtained on the allocated backhaul subframe of SN_s is calculated as $\bar{R}_b^s = \lfloor J_b^s \rfloor f(\bar{\phi}_s)$.

J_b^s is the required backhaul resource where SN_0 transmits data to SN_s. In order to avoid packet congestion, the cumulative average data rate of each base station should match each other on the access subframe and the backhaul subframe, so, $\bar{R}_a^s$= $\bar{R}_b^s$.

We substitute (3.3) and (3.5) into (3.1) to obtain the object function of PFRA:

$$max\left(\underbrace{\sum_{s \in S} |U_s + U_s'| \times \log \lfloor J_a^s \rfloor}_{\text{sub-formula 1}} + \underbrace{\sum_{u \in U} \sum_{s \in S} \rho_{u,s} \times \log \frac{f'(\bar{\gamma}_{u,s})}{|U_s + U_s'|}}_{\text{sub-formula 2}} \right) \tag{3.6}$$

When the SINR of the communication link is unchanged at the period of resource allocation, the ratio η_s of the backhaul resource to the access resource of each base station can be determined. So, the sub-formula 2 in (3.6) is a definite value. (3.6) can be solved only when the sub-formula 1 is considered and two conditions are met as below:

$$\begin{gathered} \sum_{s \in S} \eta_s \lfloor J_a^s \rfloor = \lfloor J \rfloor \\ \lfloor J_a^s \rfloor \leq \lfloor J_a \rfloor, \forall s \in S \end{gathered} \tag{3.7}$$

The sub-formula 1 can be transformed by using the equal sign constraint:

$$max \sum_{t \in D} |U_t + U_t'| \times \log \lfloor J_a \rfloor + \sum_{s \in S, s \notin D} |U_s + U_s'| \times \log \lfloor J_a^s \rfloor \tag{3.8}$$

The subset D is defined as a set of base stations that can fully use the access resource. The Lagrange multiplier formula is used to solve (3.8) and λ ($\lambda \geq 0$) is the Lagrange multiplier.

$$L(\lceil J_a^s \rceil, \lambda) = \sum_{t\in D} |U_t + U_t'| \times \log \lceil J_a \rceil + \sum_{s\in S, s\notin D} |U_s + U_s'| \times \log \lceil J_a^s \rceil \\ - \lambda \left(\sum_{t\in D} \eta_t \lceil J_a \rceil + \sum_{s\in S, s\notin D} \eta_s \lceil J_a^s \rceil - \lceil J \rceil \right) \quad (3.9)$$

The access resource $|J_a^s|$ of SN_s can be obtained with derivative in (3.9).

$$|J_a^s| = \begin{cases} \dfrac{|U_s + U_s'|}{\eta_s} \cdot \dfrac{\lceil J \rceil}{U}, s\in S, s\notin D \\ \dfrac{\sum_{t\in D} |U_t + U_t'|}{\sum_{t\in D} \eta_t} \cdot \dfrac{\lceil J \rceil}{U}, t\in D \end{cases} \quad (3.10)$$

The result of resource allocation must be in the form of integer, so the access resource of SN_s is $\lceil J_a^s \rceil = \lceil max(1, |J_a^s|) \rceil, \forall s\in S, (U_s + U_s') \neq 0$.

The iterative algorithm is used to find the smallest number of SBSs in subset *D*. First, the subset *D* only contains the MBSs. Then, make *P* as a set of SBSs in the second layer when access resource calculated by (3.10) do not satisfy the constraint condition (3.7). Finally, if the set *P* is nonempty, the SBS with most access resource is selected from the set *P* and added to the subset *D which* is updated. The process repeats until the set *P* is empty.

3.2Secondary Layer Resource Allocation

The secondary layer resource allocation is that the SBSs in the second layer allocate RBs to their UEs and the SBSs in the third layer. After the access resource J_a^s of SN_s has been calculated, the backhaul resource J_b^s is obtained by $\lceil J_b^s \rceil = \eta_s \lceil J_a^s \rceil, s\in S$.

The backhaul link cumulative rate $\bar{R}_b^{sc}$ of *u* connected to SN_{sc} is

$$\bar{R}_b^{sc} = \sum_{u\in U_{sc}} \bar{R}_{u,sc} \approx \sum_{u\in U_{sc}} \frac{\lceil J_a^s \rceil}{|U_s + U_s'|} f(\bar{\varphi}_{sc}) \quad (3.11)$$

The backhaul resource J_b^{sc} of SN_{sc} is

$$\lceil J_b^{sc} \rceil = \frac{\bar{R}_b^{sc}}{f(\bar{\varphi}_{sc})} = \sum_{u\in U_{sc}} \frac{\lceil J_a^s \rceil}{|U_s + U_s'|} \quad (3.12)$$

The access resource J_a^{sc} of SN_{sc} is

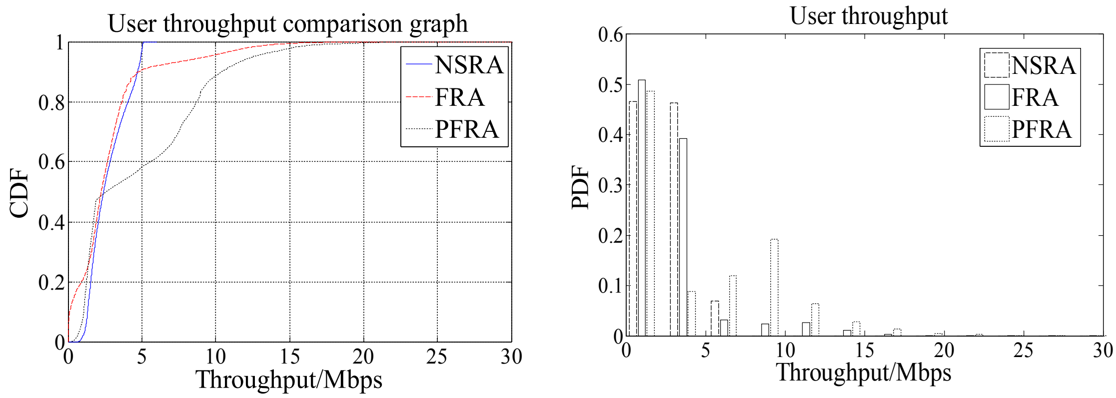
$$\lceil J_a^{sc} \rceil = \frac{f(\bar{\varphi}_{sc})}{\sum_{u\in U_{sc}} f(\bar{y}_{u,sc})} \cdot \frac{|U_{sc}|^2}{|U_s + U_s'|} \cdot \lceil J_a^s \rceil \quad (3.13)$$

It should be ensured that J_a^{sc} is less than backhaul resource J_b of SN_0, otherwise, reduce the J_a^{sc}. Thus by now, the resource allocation of the access and the backhaul links have been completed.

4. Matlab Simulation Analyses

The simulation is performed under a single cell. There is only one MBS in the cell divided into three sectors. The coverage distance of the MBS is [-1/3km, 1/3km]. We mainly simulate the downlink performance gain, focusing on the data from the core network to the UEs.

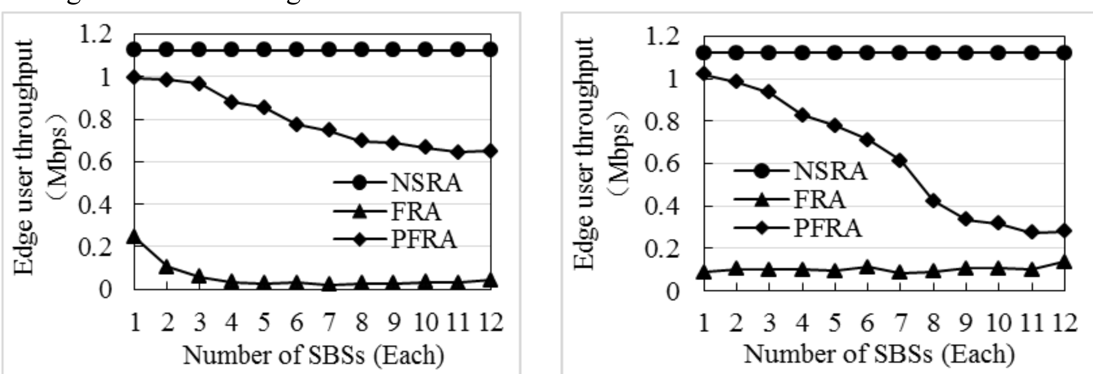
It can be observed from Figure 2 that the user rate of non-small-cell-station resource allocation (NSRA) algorithm is more concentrated, and that of PFRA algorithm and fixed resource allocation (FRA) algorithm is relatively scattered. PFRA algorithm is the best of the three schemes to improve the user rate. On the one hand, tt can reduce the number of users with low rate and increase the number of users with high rate. On the other hand, PFRA algorithm ensures that the number of users in the bottom layer is consistent with the allocation of backhaul resource, and the data rate of the backhaul link is greater than or equal as the sum of rate of the access user. The smallest resource allocation unit used in this scheme is RB with large granularity. Therefore, the rate will significantly be decreased by reducing one RB. If the smallest segmentation unit with smaller granularity is used, such as carrier [11] [12], the user throughput performance will be better.



(a) Cumulative Distribution **(b)** Probability Density Distribution

Figure 2: Comparison of User Throughput Distribution for Different Algorithms (with 5 SBSs in the second layer and 2 SBSs in the third layer)

Figure 3 shows that the edge user throughput of PFRA algorithm and FRA algorithm is less than that of the NSRA algorithm. Compared with NSRA algorithm, in PFRA algorithm, while the addition of the small base stations makes total throughput significantly increase, the interference will relatively increase. RR scheduling scheme used in this paper without considering the quality of user channel and the transmission rate may lead to small network coverage rate of PFGA algorithm.



(a) Different number of SBSs in the Third Layer **(b)** Different number of SBSs in the Second Layer

Figure 3 : Edge User Throughput of Different Layer and SBSs

5. Conclusion

The PFRA algorithm is designed in this paper for wireless hybrid hierarchical backhaul network to improve the total network throughput. The simulation results show that the PFRA algorithm is effective in improving the network throughput compared with the traditional NSRA algorithm and FRA algorithm. However, the edge user throughput of PFRA algorithm is not very satisfactory when compared with NSRA algorithm.

RR scheduling scheme used may lead to the reduction of the network coverage rate. The proportional fair scheduling scheme which takes user fairness and user rate into account will probably solve this problem and improve the network performance. That's the further study we need to do.

References

[1] Hong S, Lv C, Zhao T, Wang B, Wang J, Zhu J. *Cascading failure analysis and restoration strategy in an interdependent network*[J]. Journal of Physics A Mathematical & Theoretical, 2016, 49(19):195101.

[2] Hong S, Zhang X, Zhu J, Zhao T, Wang B. *Suppressing failure cascades in interconnected networks: Considering capacity allocation pattern and load redistribution*[J]. Modern Physics Letters B, 2016, 30(05):1650049.

[3] Hong S, Wang B, Ma X, Wang J, Zhao T. *Failure cascade in interdependent network with traffic loads*[J]. Journal of Physics A Mathematical & Theoretical, 2015, 48(48):485101.

[4] Hong S, Yang H, Zhao T, Ma X. *Epidemic spreading model of complex dynamical network with the heterogeneity of nodes*[J]. International Journal of Systems Science, 2016, 47(11):2745-2752.

[5] Hwang I, Song B, Soliman S S. *A holistic view on hyper-dense heterogeneous and small cell networks* [J]. Communications Magazine, IEEE, 2013, 51(6): 20-27.

[6] Yu S M, Kim S L. *Downlink capacity and base station density in cellular networks*[C]. Modeling & Optimization in Mobile, Ad Hoc & Wireless Networks (WiOpt), 2013 11th International Symposium on. IEEE, Japan, Aug, 2013: 119-124.

[7] Wang C X, Haider F, Gao X, You X H, Yang Y, Yuan D, et al. *Cellular architecture and key technologies for 5G wireless communication networks* [J]. Communications Magazine, IEEE, 2014, 52(2): 122-130.

[8] Access E U T R. *Physical channels and modulation*[J]. 3GPP TS, 2009, 36.211: V8.2.0.

[9] *3GPP long term evolution: principle and system design* [M]. The People's Posts and Telecommunications Press (Posts & Telecom Press), 2008.

[10] Kelly F. *Charging and rate control for elastic traffic* [J]. European transactions on Telecommunications, 1997, 8(1): 33-37.

[11] Song Q, Huang Y, Ning Z, Wang F. *Subcarrier allocation in multi-hop orthogonal frequency division multiple access wireless networks*[J]. Computers & Electrical Engineering, 2014, 40(2): 599-611.

[12] Kim B G, Lee J W. *Joint opportunistic subchannel and power scheduling for relay-based OFDMA networks with scheduling at relay stations*[J]. Vehicular Technology, IEEE Transactions on, 2010, 59(5): 2138-2148.