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Fractional Frequency Reuse and Power Control for Heterogeneous Wireless Networks Using Lagrange and Gradient Descent Method

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Abstract - Among the fast growing wireless network capacity and coverage demands, the heterogeneous wireless networks have emerged in a great way. More advanced interference coordination and radio resource management schemes are necessary to achieve a high network capacity. This is the result of the co-deployment of high power and low power nodes in the same network using the same spectrum, In this paper, an optimal fractional frequency reuse and power control scheme that can efficiently coordinate the interference among high power and low power nodes is proposed. In order to carry out the sum of the long term log-scale throughput among all the user equipments (UEs) and also to maximize it, the above mentioned scheme can be optimized. The Lagrange dual function is first derived for the proposed optimization problem and the Gradient descent method is then used to search the optimal solution for the convex dual problem. The optimal solution for the dual problem is accepted as the optimal solution for the primal problem, as the system exhibits a strong duality condition. The proposed scheme can greatly improve the wireless heterogeneous network performance on system capacity and user experience.

Index Terms— Keywords - Heterogeneous network, fractional frequency reuse, convex optimization, power control.

I. INTRODUCTION

Wireless traffic volume has emerged and is expected to expand tremendously in the next few years, followed by the new generation devices like netbooks, smart phones, and other mobile Internet devices; and bandwidth consuming applications such as video streaming and also mobile video streaming. There is a huge gap between the new air interface development pace and the growth rate of customer's needs. As the link efficiency approaches its fundamental limits, to meet the demand of mobile data traffic, the future wireless systems are expected to be heterogeneous networks with base stations of diverse sizes and types. In wireless systems, one primary problem affecting the user experience and limiting the system capacity is interference. Due to the use of Orthogonal Frequency Division Multiple Access (OFDMA) in most of the new wireless systems, the intra-cell users are assumed to be orthogonal to each other and the primary source of interference is inter-cell interference.

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Inter-cell interference coordination (ICIC) in the traditional homogeneous wireless network has been well studied and is most effectively achieved via different static or pseudo- dynamic frequency reuse schemes based on the long-term channel statistics and user distributions.

The authors studied the problem of optimal Fraction Frequency Reuse (FFR) and resource allocation in an OFDMA system. The problem is formulated as sum-power minimization problem subject to minimum rate constraints, which was solved by using Lagrange dual decomposition theory at a reasonable computational cost evaluated two main types of FFR deployments: Strict FFR and Soft Frequency Reuse (SFR) in an OFDMA system. Relevant metrics were discussed, including, throughput of the network, spectral efficiency, outage probability and average cell-edge user signal-to-interference-plus-noise ratio (SINR).

Unlike the traditional homogeneous networks, the interference coordination problem is significantly more challenging in a wireless heterogeneous network. In addition to inter-cell interference, cells from different layers, i.e., macro- or micro- layers, have different

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transmission powers and are overlaid with each other, resulting in new and complicated interference scenarios. The complex combination of cells and layers requires smart optimization and resource management solutions. Inter-layer and inter-cell interference coordination is a strategy to improve the performance of a heterogeneous network by having cells from the same layer as well as from different layers to coordinate their resources so that interference is minimized. Motivated by this requirement, applications of FFR in heterogeneous networks have been investigated. Specifically, further it has been proposed about the specific strict FFR schemes and investigated the optimal frequency reuse factor and power allocation to maximize the spectrum efficiency. Strict FFR significantly reduces interference but at the cost of loss in spectrum efficiency considered both strict and soft FFR and analyzed the coverage of a multi-tier heterogeneous network. Best-power based mobile association was assumed and is the key in obtaining the analytical results on network coverage. We have shown that using different frequency reuse schemes between macro- and micro-layers can effectively alleviate the interference and achieve high system throughput and good SINR distributions in a heterogeneous network.

In a wireless heterogeneous network, the interference scenarios have been tightly coupled with the mobile association scheme. In conventional homogeneous networks, where all base stations (BSs) have the similar transmit power level and processing capability, a best-power based association scheme works well. In heterogeneous networks, due to the disparity in the transmit powers between the BSs and the micro-nodes, most of the UEs receive stronger signals from the BSs than from the micro-nodes. Therefore, to fully exploit the benefits of the heterogeneous networks, a new radio resource management scheme that jointly considers mobile association, interference coordination and power control is desirable. In this paper, we propose an optimal fractional frequency reuse and power control scheme that can achieve both spectrum efficiency and user fairness. The proposed framework optimizes the fractional frequency reuse parameters by maximizing the sum of long term log throughput. Simulation results show that the network performance can be greatly improved by the proposed optimization framework.

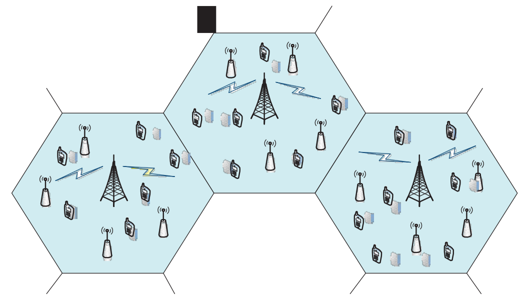

Fig 1: Downlink communication model in a cellular network.

II. SYSTEM MODEL

Here the system model represents a wireless heterogeneous network model. Fig. 1 shows a downlink communication in a cellular network. In the figure the network is divided into number of cells and each cell is divided into several sectors with one Base Station (BS) and multiple micro-nodes which are deployed in each sector. A BS represents a macro-node. The communication link has been termed between a BS and a UE as a direct link and also the link between a micro-node and a UE as an access link. The micro-node considered, is being transmitted with a low power and is equipped with a complete set of radio resource control functions. The deployment of micro-nodes introduces smaller cells overlaid with the conventional cellular system and effectively enhances the cellular network coverage and capacity.

Here, the total number of sectors is denoted by N_C, followed by the number of uniformly distributed micro- nodes in each sector as $N_{\mathbf{r}}$. The total number of uniformly distributed UEs in the system is denoted by N_u. Here, we use $N_{o,i}$ to denote the BS in the sector i and $N_{j,i}$ to represent the micro- node in the sector i. P_b and P_r represents the default transmission power of the BS and the micro-node. In this model, the transmission power of the entire BS is assumed to be the same. OFDMA is the basic physical layer transmission scheme on both direct and access links. The entire frequency band $\mathbf{f}$ is divided into F equally-sized sub-bands and radio resources are allocated in the unit of sub-band. Due to the lower transmit power of the micro nodes; the micro-node footprint is much smaller than that of a BS. As a result, not many UEs can fall into micro-node's coverage to utilize the micro- node resources. Instead of attaching to the node that provides the strongest downlink power, the UE can attach to the node based on a biased downlink received power. To address

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this, we can either serve the UEs in the extended coverage with the orthogonal frequency bands from the neighboring BSs or reduce the transmit power of the neighboring BSs. The first approach eliminates inter-layer interference completely but may not efficiently utilize the radio resources. The second approach reduces the inter-layer interference for all the UEs attached to the micro-nodes but at the cost of possibly impairing the quality-of-service of the UEs attached to the BSs, especially the UEs at the edge of the BS cells.

In order to achieve both high spectrum efficiency and good user experience, fractional frequency reuse (FFR) with proper power control as shown in Fig. 2 is proposed in this paper. We divide the total sub-bands F into two parts, f_1 and f_2 with size F_1 and F_2, respectively. In f_1, BSs transmit at a reduced power αP_b ($0 < \alpha < 1$) to the cell center UEs while micro-nodes transmit at the full power to the UEs located at the edge of the micro-node cells. In f_2, both BSs and micro-nodes transmit at their respective full powers. BSs transmit to the BS cell edge UEs while micro-nodes transmit to the micro-node cell center UEs. A frequency partition coefficient β is defined as $\beta = F_1/F$. The proposed FFR scheme aims to not only protect cell edge UEs but also efficiently utilize the radio resources.

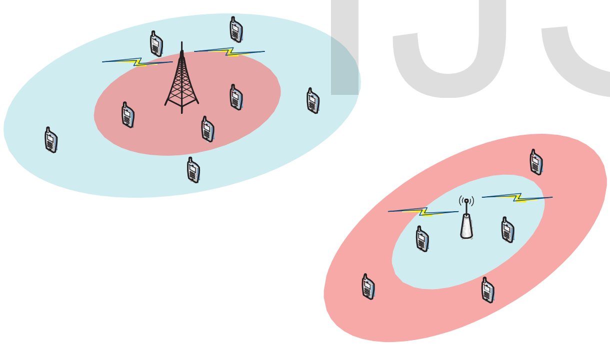

Fig. 2 Illustrate of frequency fraction reuse scheme.

UE as $h_{k,0,i}$, and the channel gain between node $N_{j,i}$ and the kth UE as $h_{k,j,i}$. The channel gain considered in this paper includes path loss and shadowing. The received signal- to-interference-noise-ratio (SINR) of the UEs, under the pro- posed fractional frequency reuse scheme, can be expressed as follows.

$$SINR^{f1}_{k,o,i} = \frac{\alpha Pb\,|hk,0,i|^2}{\sum_{i' \neq i} |hk,0,i'|^2 \alpha Pb + \sum Nc \sum Nr\, |hk,j,i|^2 Pr + No} \quad \text{------- (1)}$$

$$SINR^{f2}_{k,o,i} = \frac{Pb\,|hk,0,i|^2}{\sum_{i' \neq i} |hk,0,i'|^2 Pb + \sum Nc \sum Nr\, |hk,j,i|^2 Pr + No} \quad \text{------- (2)}$$

$$SINR^{f1}_{k,j,i} = \frac{Pb\,|hk,j,i|^2}{\sum_{i' \neq i} |hk,j,i'|^2 Pb + \sum Nc \sum Nr\, |hk,j,i|^2 Pr + No} \quad \text{------- (3)}$$

$$SINR^{f2}_{k,j,i} = \frac{\alpha Pb\,|hk,j,i|^2}{\sum_{i' \neq i} |hk,j,i'|^2 \alpha Pb + \sum Nc \sum Nr\, |hk,j,i|^2 Pr + No} \quad \text{------- (4)}$$

Here, $SINR^{f1}_{k,0,i}$ is the SINR value when UE k is associated with $N_{0,i}$'s cell center while $SINR^{f2}_{k,0,i}$ is the SINR value when UE k is associated with $N_{0,i}$'s cell edge. $SINR^{f1}_{k,0,i}$ and $SINR^{f2}_{k,j,i}$ are similarly defined. With the help of the SINR values, the unit achievable data rate in terms of bit/s/Hz for the kth UE.

III. PROBLEM EVALUATION

In this paper, for maximizing the long-term system throughput and along with that, to ensure good user experience, it is required to design an optimal FFR methodology. Hence, we have to calculate the value of β2 i.e., the optimal partition of the frequency sub-bands f1 and f2 and the optimal transmit power of the BSs in the f1 sub band, i.e., the value of α. The FFR optimization scheme is closely related to the mobile association scheme used. There is a way for carrying out this methodology jointly, and this can be carried out by joining the optimizing FFR and mobile association, which would be highly complicated. The above mentioned policy could be also mathematically intractable and impractical for implementation. Thus we will first decide the mobile association scheme offline, based on which the proposed scheme can be jointly optimized. In the conventional homogeneous networks, best-power based mobile association scheme is often applied, where the kth UE is associated with the best node $N_{(j^*, i^*)}$.

$$(j^*, i^*)_k = \arg_{i \in \{1,\ldots,Nc\},\, j \in \{o,1,\ldots,Nr\}} (P_{k,j,i})\, |hk,0,i|^2 \quad \text{------------- (5)}$$

Where $P_{k,j,i}$ is the corresponding node transmission power. In the heterogeneous networks, due to the transmit power disparity between the BS and the micro-node, most of the UEs will be associated with the BSs if the best power based association scheme is used.

The micro-node utilization will be low and the advantage of using micro-node in improving the spectrum efficiency and coverage of the network could not be fully exploited. To balance the traffic load between the BSs and the micro-nodes, we apply range-expansion based association scheme, which uses a bias to compensate the power difference between BSs and micro-nodes, so that more UEs can be associated with micro-nodes.

The optimization of FFR scheme is pseudo-static, i.e., the decision is based on the long-term statistics instead of short-term information. This is consistent with the most FFR scheme designs in the wireless networks. Thus the resources allocated to each UE defined in the following are the average allocation over a certain time period. So is the throughput. For UE k associated with $N_{0,i}$'s cell center (or cell edge), the allocated resources in the unit of sub-band are denoted as $n^{f1}_{k,0,i}$ (or $n^{f2}_{k,0,i}$). Similarly, for UE k associated with Nj,i's cell center (or cell edge), the allocated resources in the unit of subband are denoted as nf1 k,j,i (or $n^{f2}_{k,j,i}$).

IV. CONCLUSION

In this paper, we investigated about the optimal downlink radio resource management in the wireless heterogeneous networks based on the heterogeneous wireless network model. A fractional frequency reuse and power control scheme has been proposed in order to coordinate the interference between the BSs and the micro-nodes. Here, an optimal algorithm has been developed to achieve both spectrum efficiency and user fairness. The proposed optimization framework jointly optimizes the fractional frequency reuse parameters and the frequency resource allocation among the UEs. To solve the optimization problem, a two-loop optimization algorithm has been proposed, where a close-form solution of the resource allocation can be derived. Further the results can indicate that mobile association scheme has a high impact on the network performance. As a future research direction, a joint optimization of the mobile association and fractional frequency reuse can be investigated.

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