Data Offloading in Two-Tier Heterogeneous Cellular Networks: Stackelberg Game Based Approach

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Abstract

In two-tier heterogeneous networks (HetNets), picocells can be offered an economic incentive in order to offload traffic from high-power macrocell which is usually overload. This becomes important in order to maintain efficient operation of the network and generate benefit tradeoff between macrocell and picocells. The benefit to picocells comes from the economic incentive of macrocell and the benefit to macrocell is achieved reducing the load and saving spectrum. However, two important challenges are posed in this cooperation: 1) How much economic incentive can be offered by macrocell, and 2) how much offloading traffic volumes can be admitted by the picocells. In this paper, we propose a novel game based approach for data offloading scheme to determine the amount of economic incentive a macrocell should offer to picocells and to determine how much traffic each picocell should admit from macrocell. In our proposal, a two-stage non-cooperative Stackelberg game theory is applied to optimize the strategies of both macrocell and picocells in order to maximize both of their utilities.

I. Introduction

Wireless data traffic has seen significant growth in volume in recent years due to development of the infrastructure of mobile market (e.g., new generation of wireless network and mobile devices in 4G and 5G) [1]. Moreover, it has a fundamental trend in traffic pattern shifting from data-centric to video-centric. This considerable increase leads to new serious challenges for the mobile network operators (MNOs) who have to enhance and maintain their network infrastructure accordingly. However these operations are often costly and time-consuming [1]. MNOs must find alternative methods to address this problem. One of the approach used by the MNOs is to install small cells to enhance the capacity of cellular networks which is termed as heterogeneous networks. Installation of small cells under the coverage of macrocell causes interference due to use of same frequency bands. Mobile data offloading has been considered as an effective approach to cater with the bursty traffic of cellular networks.

In traditional heterogeneous networks, data traffic of macrocells is deliberately routed to the complementary networks, namely small cells such as picocells, femtocells, or WiFi networks [1][2][3] in order to offload its bursty traffic to small cells. Nevertheless, mobile data offloading may reduce the heavy load of macrocell but it also leads to congestion in small cells due to the limited resource in co-channel deployments and small coverage area of small cells. Consequently, it is necessary to have an efficient resource partitioning mechanism in order to achieve optimal data offloading.

The rest of the paper is organized as follows: Section II introduces the network model and defines the problem. In section III, we propose and analyze the data offloading scheme based on the Stackelberg Game theory. Numerical results are illustrated in section IV. Finally, we conclude our work in section V.

II. System model and Optimization Problem

We consider a downlink two-tier heterogeneous network with a MBS, a set $\mathcal{P}$ of APs, and M is the size of set $\mathcal{P}$. Both MBS and APs use the same orthogonal frequency bands to transmit data. MBS and each AP serve its own group of mobile users (MUs) which are randomly distributed within the MBS and APs' coverages with infinite traffic sources. We study for one time period. The MUs' location and traffic may change over time but for simplicity they are considered fixed within each period.

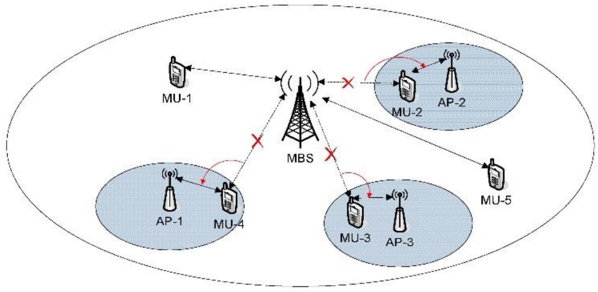

Fig.1. System model

Let l_m denote the traffic volume that AP m can admit from MBS. Let l_0 denote the total MBS's traffic that cannot be offloaded to any AP, i.e., those generated by all MUs of MBS not in coverage of any AP (e.g., MU-1 and MU-5 in Fig. 1). The traffic profile of MBS is denote by $\mathbf{l} \triangleq (l_0, l_1, ..., l_m)$. Fig. 1 illustrates our network scenario, where the large circle is the coverage area of macrocell, and small circles are the coverage areas of picocells. It can be seen that these small circles are overlapping; hence, there is intra-cell interference among picocells. In this example, the traffic of MU-2 can be offloaded to AP-2, the traffic of MU-3 can be offloaded to AP-3, and the traffic of MU-4 can be offloaded to AP-1.

III. Stackelberg Game Theory Analysis

The interaction between the MBS and picocell APs can be characterized as a two-stage non-cooperative Stackelberg game [4][5][6] model as shown in Fig. 2. The MBS publishes the economic incentive in Stage I, and picocell APs respond with their traffic admission abilities in Stage II. All picocell APs want to maximize their total utilities by optimizing the traffic offloaded they can admit according to the economic incentive offered from MBS. The MBS wants to maximize its utility by setting the right economic incentive to satisfy the admit abilities of picocell APs.

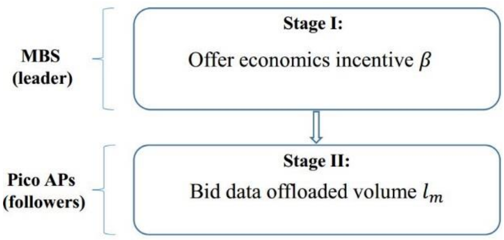

Fig. 2. Two-Stage Stackelberg Game Model

A. Stage II: Picocell Access Point's Strategy

The Pico APs can be modelled as followers. The aim of the the proposed scheme is to maximize the picocell's overall utility. The payoff function of each AP $m \in \mathcal{P}$ can be formulated as follows

$$U_m(l_m) = \beta \frac{l_m}{\sum_{n\in\mathcal{P}} l_n} - \rho_m l_m \quad (1)$$

Where ρ_m and β are unit power cost for offloading traffic from MBS, and the economic incentive for offloading traffic to all pico APs, respectively. l_m is offloaded traffic pico AP m can offload. This payoff function can be explained that the economic incentive each pico AP achieves is proportional to the offloaded traffic it made for the MBS minus the linear cost it incurs to offload this traffic.

$$\frac{\partial U_m}{\partial l_m} = \frac{\beta \sum_{n\in\mathcal{P}, n\neq m} l_n}{\left(\sum_{n\in\mathcal{P}} l_n\right)^2} - \rho_m \;, \; \frac{\partial^2 U_m}{\partial^2 l_m} = \frac{-2\beta \sum_{n\in\mathcal{P}, n\neq m} l_n}{\left(\sum_{n\in\mathcal{P}} l_n\right)^3} < 0 \quad (2)$$

The second order derivative of U_m with respect to l_m is always negative, therefore $U_m(l_m)$ is concave in l_m. The best response for the non-cooperative Stackelberg game is the unique optimal solution for the following optimization problem:

$$\begin{aligned} &\underset{l_m}{\text{maximize}} \quad U_m(l_m) \\ &\text{subject to} \quad l_m \le c_m, \end{aligned} \quad (3)$$

where c_m is the capacity of the pico AP m. We assume c_m is fixed over the time period. The constraint means that the offloaded traffic of a pico AP can not exceed its capacity.

The best response of each pico AP is given as follow.

$$l_m^* = \left[\frac{\beta(M-1)}{\sum_{m\in\mathcal{P}} \rho_m} \left(1 - \frac{(M-1)\rho_m}{\sum_{m\in\mathcal{P}} \rho_m} \right) \right]_0^{c_m} \quad (4)$$

B. Stage I: Macrocell Base Station's Strategy

The MBS can be modelled as leaders. The overall utility function of MBS can be formulated as follows

$$U_{MBS}(\beta) = \delta \sum_{m\in\mathcal{P}} l_m - \beta \sum_{m\in\mathcal{P}} l_m, \quad (5)$$

where δ and β are unit spectrum save by offloading traffic to pico APs, and the economic incentive for offloading traffic to all pico APs, respectively.

Based on the knowledge of the pico APs's behavior, the MBS aims to maximize it net profit by solving the following optimization problem

$$\underset{\beta}{\text{maximize}} \quad U_{MBS}(\beta) \quad (6)$$

Substituting (4) into the MBS's utility function (5) we obtain:

$$\underset{\beta}{\max.} \quad \frac{(\delta-\beta)\beta(M-1)}{\sum_{m\in\mathcal{P}} \rho_m} \sum_{m\in\mathcal{P}} \left(1 - \frac{(M-1)\rho_m}{\sum_{m\in\mathcal{P}} \rho_m} \right) \quad (7)$$

It is straightforward to show that the problem (7) is convex optimization problem, hence we can obtain global optimal value of the economic incentive β^*.

IV. Numerical Results.

In order to validate our proposition, we consider the scenario as shown in Fig. 1. It consists of one macrocell and multiple picocells. We vary the number of picocells in the system to evaluate the performance of our proposal and find the optimal number of picocells supported by the network. We for our simulation gradually increase the number of picocells from the range of 1 to 20 as shown in Fig. 3.

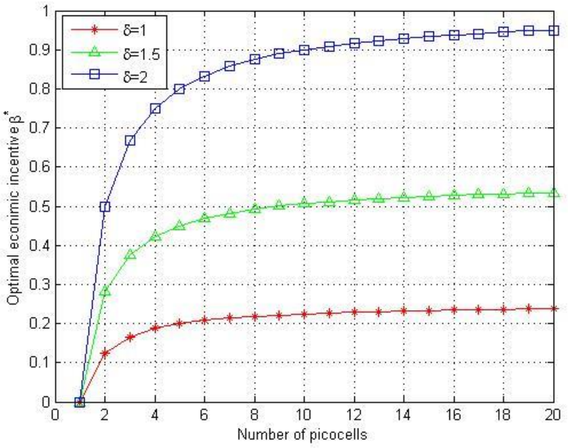

Fig. 3. Number of picocells vs. Optimal economic incentive

Fig. 4 shows the MBS's utility achieved with different value of economic incentive β, and three cases of unit spectrum save δ. It can be seen that lower value of δ gives us a lower utility for MBS.

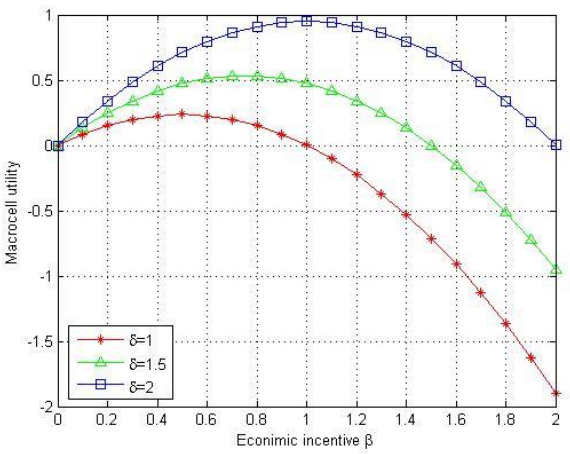

Fig. 4. Economic incentive vs. Macrocell utility

V. Conclusions

In this paper, we have developed a game theoretic model for solving data offloading problem in co-channel two-tier heterogeneous networks, in which MBS wishes to offload its volume of traffic to picocells which underlay in its coverage. We did a number of simulation by varying the number of picocells in the HetNet to find the optimal economic incentive to the picocells by MBS. In future we plan to investigate a user association scheme, the scheme would identity which offloaded users should associate with which APs in order to obtain the optimal user association such that the offloading traffic is maximized.

Acknowledgment

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