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Price-based resource allocation for self-backhauled small cell networks☆

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ABSTRACT

Heterogeneous cellular networks are promising solutions to address the need for the exponentially increasing data traffic demands by ensuring an acceptable level of quality of service. In such networks, base stations with different cell sizes serve the cellular areas (i.e., macro cells along with small cells). The access technologies of such base stations can be different as well. Small cell access points (SAP) are typically connected either directly to the core network through a wired link or to a macro-cell base station through a wireless backhaul link. In this paper, we consider the scenario where the SAP is connected to a macro-cell base station through a wireless backhaul link operating at the same frequency band as the access links from the SAP to its users. We consider amplify and forward (AF) protocol under both full/half duplex transmission modes for the SAP. Under such circumstances, we study the price-based resource allocation where the SAP charges each user equipment (UE) proportional to the amount of the power it allocates for transmission to that UE. A Stackelberg game is employed to model and investigate the joint utility maximization problem of the SAP and UEs. In our game model, the SAP is the leader and the UEs are the followers. We formulate the utility maximization problems for both the leader and the followers as optimization problems. We consider two pricing schemes, namely non-uniform and uniform. Moreover, we present a condition which gives a proper criterion for resignation of the UEs from the proposed Stackelberg game when transmitted power of the SAP is limited. We prove that both sub-games are convex optimization problems which ensures their tractability. We also propose a novel algorithm to obtain the optimal prices of Stackelberg equilibrium of the game. Numerical results validate the efficiency of our proposed priced based resource allocation scheme.

1. Introduction

Mobile data traffic has been growing dramatically in recent years. An ordinary smartphone is expected to generate approximately 1.3 GB data traffic per month in 2015, which leads to a 11-fold increase in global data traffic in 2015 in comparison to 2013 [1]. To alleviate this data traffic storm, mobile operators have increased the capacity of the radio access and backhaul links not only through development of new technologies but also via operating at higher and wider frequency bands. Despite of all these efforts, the demand is expected to exceed the capacity of the fourth generation cellular networks in near future [1,2].

The use of small cell access points (SAP) operating at the same frequency band with the same access technology or different frequency bands with different access technologies are attractive solutions to cope with the explosive data traffic demand. Networks including base stations with various sizes (i.e., macro cells along with small cells) and possibly various access technologies is called heterogeneous networks. Heterogeneous networks are attractive solutions providing better quality of service (QoS) and support higher number of users. SAPs are connected to the core network through a wired or wireless link. Wired backhaul links which employ optical transmission technology are costly. Microwave backhaul links require extra frequency bands which is costly as well. One solution to solve this issue is to use a SAP capable of communicating with the macro base station (BS) at the same frequency band that it uses for the users. In the downlink channel, the SAP would receive data from the macro BS while simultaneously transmitting the data to the UEs. In this method, the SAP uses the same channel for access and backhaul. Therefore, there is no

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need for a separate backhaul channel which decreases the cost and capital expenditure (CAPEX) [3–6]. This is called a *self-backhauled* SAP.

The enabling technology behind the self-backhauled SAPs is *full duplex*(FD) operation of the SAP transceivers. We shall notice that there is no need to change BS or UEs. Authors in [7] have designed and implemented the first real FD WiFi radio using single antenna for simultaneous transition and reception on the same channel. They have proposed novel analog and digital self-interference cancellation techniques that cancel the self-interference and enables FD mode of operation. uplink, downlink, and backhaul transmissions. Self-backhauling is particularly efficient when coupled with FD relaying. Antenna design, as well as cancellation in radio frequency and digital domains at an FD relay enables reuse of the same resources for backhaul and access hops. The use of radio resources in the self-backhauling and access hops can be coordinated to maximize end-to-end performance [8].

Recently, different aspects of pricing and economics of heterogeneous cellular networks and mobile data offloading are investigated. In [9], authors investigated the virtual resource allocation issues in small cell networks with FD self-backhauls and virtualization. They formulated the virtual resource allocation problem as an optimization problem by maximizing the total utility of mobile virtual network operators (MVNOs). In [10], authors studied the economics of mobile data offloading and proposed a Stackelberg game model for multiple BSs and APs. The authors in [11] studied the economic incentive issue by using an iterative double auction mechanism. In [12], authors proposed an economic framework and formulated the interactions between the users and the BS by using a Stackelberg game model. In [13], a well described price-based resource allocation for a two tier spectrum sharing femtocell network is considered. A Stackelberg game was formulated to study the joint utility maximization of the macrocell and femtocell and a closed form solution for the Stackelberg Equilibrium of the game is proposed. In [14], a price-based resource allocation for a hybrid spectrum femtocell network is investigated using Stackelberg game. In [15], authors studied the economic incentive issue by using the cooperative game framework, precisely Nash bargaining model. They used a one-to-one bargaining model between the mobile operator and fixed-line operator. In [16], the authors consider a capacity maximizing power allocation based on a Stackelberg game, where the MBS is the leader and the FBSs are assumed as followers. The game is formulated as a mathematical program with equilibrium constraints, and an iterative algorithm has been presented to reach the Stackelberg equilibrium. Most of these works only consider SAPs with wired backhaul which is cost-prohibitive.

In this paper, we investigate a price-based power allocation in an imperfect self-backhauled FD SAP using Stackelberg game. We also consider the half duplex SAP as a benchmark. A Stackelberg game is proposed in which the SAP plays as the leader and the UEs are the followers. The SAP has limited power and shares it between the UEs. Moreover, the SAP uses AF protocol to transmit the information of the UEs. The UEs need to pay based on the portion of the power they use from the SAP. The higher the power SAP uses for transmission to each UE, the higher its data rate as well as the higher its payment to the SAP. Our goal is to jointly maximize the utility of the SAP and UEs. In the first stage of the game, the FD SAP proposes a set of prices to the UEs by maximization of its utility subject to an aggregate power constraint. Then, each UE calculates its optimal downlink transmit power for the given prices. We consider two pricing schemes: *non-uniform pricing or discriminatory pricing* in which the SAP imposes different prices to different UEs, and *uniform pricing or nondiscriminatory pricing* in which the same price is imposed to all UEs. In the paper, we will use these words interchangeably. In this paper, both

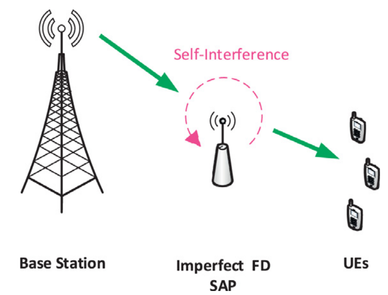

Fig. 1. System model for the FD SAP.

half duplex and full duplex transmission modes are considered for comparison.

To find the Stackelberg equilibrium, backward induction method is used. The UEs' sub-game is proved to be a convex optimization problem and a closed form solution is proposed. The leader's sub-game is also proved to be a convex optimization problem. We propose an algorithm to find the best response of the leader subgame. At the end, the proof of optimality of the algorithm is proposed. In addition, in case that the transmitted power of the SAP is limited, some UEs should resign from the game. We present a condition so that based on that, UEs can decide whether resign the game or not. Each UE can check the proposed price with a given threshold, and decide to resign the game or not. To the best of our knowledge, this is the first work which investigates the price-based resource allocation in an imperfect self-backhauled FD SAP using Stackelberg game. Most of works which investigated the pricing and economics of SAPs and heterogeneous networks assumed that the SAPs use wired backhaul. The underlying self-backhauld system eliminates the need for a separate backhaul solution and also separate frequency band (whether licensed or unlicensed), that can effectively decrease the cost and complexity of rolling out a small cell network [6].

The rest of the paper is organized as follows. The system model is described in Section 2. We formulate the Stackelberg game problem in Section 3. Section 4 presents the Stackelberg equilibrium point of the proposed game under both pricing schemes and the numerical results are presented in Section 5. Finally, Section 6 concludes the paper.

2. System model

We consider a two-tier heterogeneous network consisting of one macro BS and N UEs. We assume there is a SAP within the coverage area of the BS. As shown in Fig. 1, due to the distance between the BS and the UEs, the BS can route information through SAP to provide better QoS for the UEs. Since the SAP is a selfish node, it charges the UEs for forwarding their information. Each UE adjusts its downlink power (i.e., rate) taking into the account the price charged by SAP. The SAP aims to maximize its revenue under the aggregate power constraint on the downlink power. In this paper, we focus on the downlink transmissions but it is worth pointing out that this scenario can be extended to the uplink direction with slight modifications.

We assume that the SAP uses AF protocol to transmit the information of BS to UEs. For AF protocol, the SAP amplifies its received information and forwards it to the UEs. Let γ_0 and γ_i, $\forall i$ denote the channel gain from BS to SAP and from SAP to UE i, respectively. The additive noise is modeled as white Gaussian with zero mean and unit variance. Each slot is called a frame and T_f denotes the frame duration. The data link packets are divided into frames at the physical (PHY) layer. The frame duration is assumed to be less than the fading coherence time. So we assume channel gains will