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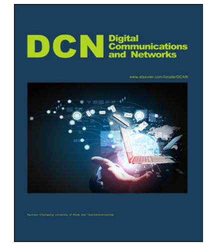

Joint duplex mode selection, channel allocation, and power control for full-duplex cognitive femtocell networks ☆

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Abstract
In this paper, we aim to maximize the sum rate of a full-duplex cognitive femtocell network (FDCFN) as well as guaranteeing the quality of service (QoS) of users in the form of a required signal to interference plus noise ratios (SINR). We first consider the case of a pair of channels, and develop optimum-achieving power control solutions. Then, for the case of multiple channels, we formulate joint duplex model selection, power control, and channel allocation as a mixed integer nonlinear problem (MINLP), and propose an iterative framework to solve it. The proposed iterative framework consists of a duplex mode selection scheme, a near-optimal distributed power control algorithm, and a greedy channel allocation algorithm. We prove the convergence of the proposed iterative framework as well as a lower bound for the greedy channel allocation algorithm. Numerical results show that the proposed schemes effectively improve the sum rate of FDCFNs.

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1. Introduction

The femtocell technology is initially proposed as an effective solution for enhancing coverage by deploying indoor femtocell base stations (FBS) that are connected through wired links such as cable modem or Digital Subscriber Line (DSL). The short transmit–receive distance results in high signal to interference plus noise ratio (SINR), and the small coverage area enables dense spatial spectrum reuse, which both contribute to high spectrum utilization. Recently it has been recognized as a key technology by Qualcomm for meeting the 1000 $\times$ data challenge, i.e., the predicted astounding 1000 $\times$ increase in mobile data in the near future [2]. However, due to the current spectrum scarcity problem, femtocells are more likely to operate on the same spectrum band with the existing macrocells, resulting in cross-tier interference (between femtocells and macrocells) and inter-femtocell interference (among femtocells). Interference management is critical for the success of this technology.

The cognitive femtocell network (CFN) was proposed as a solution to the interference problem [3,4]. In general, the macrocell users (MU) are regarded as primary users (PU) and the femtocell users (FU) are regarded as secondary users (SU). The FBS's periodically sense the spectrum usage of MUs and allocate the unoccupied channels to FUs. The previous research works aim to improve the performance (such as throughput, capacity, and energy efficiency) of CFN as well as guaranteeing the QoS of both MUs and FUs. In [5,6], spectrum and power allocations in a CFN are formulated as optimization problems, with the objectives to maximize capacity and energy efficiency, respectively. In [7], a strategic game model was introduced by setting the payoff of a femtocell as the expected number of resource blocks (RB) without interference. With this mechanism, each femtocell makes rational decisions on the spectrum usage pattern and the interference between femtocells is mitigated. Another game theoretic mode was proposed in [8], where the penalty of a femtocell is determined by excessive usage of RBs and transmission power. The femtocells are thus discouraged to occupy excessive RBs and transmit with high power, resulting in mitigated interference.

A general approach to address the interference problem is to restrict the spectrum and power usage of femtocells. However, when the number of MUs or the number of femtocells in the CFN is large (e.g., in a hotspot), the spectrum allocated to each femtocell could be limited. As the femtocell technology is expected to provide high data rate services to FUs, the limited spectrum resource may be insufficient to guarantee their QoS. To remedy this disadvantage, more efficient spectrum reuse is required. With the recent development of self-interference suppression technology, a wireless transceiver is able to simultaneously transmit and receive signals on the same channel, yielding a full-duplex (FD) transmission pattern [9]. Theoretically, an FD transmission could double the system capacity, making it a promising approach to improve spectrum utilization. In [10], an FD OFDMA based multi-cell network was investigated, in which the FD empowered BS simultaneously serves two cellular users on the same channel. Despite the presence of inter-cell and intra-cell interference, the results show that the capacity can be enhanced by 86% in the uplink and 99% in the downlink.

The successful use of FD in cellular network motivates us to integrate this technology into the CFN. This is a more challenging case due to the more complicate interference scenarios in a CFN. Similar to the cellular network, an FBS in the CFN can simultaneously serve a pair of FUs on the same channel, resulting in the improved spectrum utilization. However, due to the limited processing capability and battery capacity of mobile device, self-interference suppression may not be applicable to femtocell user equipments (FUE). For the two users that use the same channel, the uplink signal of one user causes interference to the downlink of the other user. To control such intra-femtocell interference, it is necessary to carefully schedule the FUs that are paired for FD transmission. When the intra-femtocell interference is strong between FUEs, the half-duplex (HD) would be a better choice. Therefore, the duplex mode selection strategy and channel allocation of femtocells should be carefully designed to achieve high capacity as well as mitigating intra-femtocell interference.

In this paper, we consider a CFN integrated with FD functionality. In such a full-duplex cognitive femtocell network (FDCFN), we aim to maximize the sum rate of FUs as well as guaranteeing the QoS of both FUs and MUs in the form of a minimum SINR requirement. The goals are achieved through duplex mode selection, distributed power control, and channel allocation. The main contributions of this paper are summarized as follows:

- We incorporate the FD and CR technologies into femtocell networks, and develop a holistic formulation of the joint duplex mode selection, power control, and channel allocation problem in an FDCFN.
- We first consider power control over a pair of channels, and propose two optimal power allocation schemes that can be used in sparse and dense femtocell deployment scenarios, respectively.
- For the case of multiple channels, we propose an iterative framework that jointly solve the duplex selection, power control, and channel allocation problems, and obtain the near optimal solution. We also prove the guaranteed convergence of the proposed framework.
- We propose a duplex mode selection strategy for FDCFN. The FUE pairing is formulated as a roommate matching problem, and we develop an effective algorithm to solve the matching problem. The duplex mode selection is based on the pairing result to achieve high capacity gains.
- We employ the SCALE (Successive Convex Approximation for Low-complExity) algorithm to solve the power control in FDCFN with a distributed approach.
- We propose a greedy channel allocation algorithm for the FDCFN based on the pairing result and derive a performance lower bound.
- The proposed schemes are evaluated with simulations and comparison with several benchmark schemes, where superior performance of the proposed schemes is observed.

The remainder of this paper is organized as follows. The problem formulation is described in Section 2. The power control over a pair of channels is discussed in Section 3. The joint duplex mode selection, power control, and channel