Decentralized spectrum sharing with beamforming in two-tier femtocell networks

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Abstract—Two-tier overlay networks that consist of a conventional macrocell network and femtocell hotspots offer an economical solution for high capacity and extended coverage. However, wireless interference across tiers significantly degrades network performance by restricting spectrum reuse. In this paper, we explore schemes to mitigate cross-tier interference using beamforming in overlay networks. In our model, femtocells can operate with frequency spectrum that is either shared with or separated from the macrocell. The enhanced signal to interference ratio (SIR) from beamforming can contribute to the shared-spectrum population of femtocells and thus improve the spectrum efficiency. We develop a decentralized scheme that solves the spectrum sharing problem to maximize total cell capacity. Through performance evaluation, we show that our proposed scheme significantly improve cell capacity in two-tier overlay networks.

I. INTRODUCTION

Recently, a personal-use indoor base station, femtocell, has gained considerable attention for extended in-home coverage and high-speed wireless broadband services, where usual macrocell system can only provide degraded service or no coverage at all. The cells with different sizes can be deployed in a hierarchical cell structure to provide multilayer network connectivity [1], [2]. Macrocell is deployed as one radio tier to cover wide areas (300–2000 meters), and femtocells are embedded inside macrocell to supply sporadic coverage (10–50 meters). The benefits for this arrangement are capacity gain, better coverage, and reduced battery consumption [3].

The cross-tier interference caused by active users can lead to unacceptable performance degradation over heterogeneous overlay network links. As a solution, the bandwidth spectrum is divided into two separate bands and each tier operates in its dedicated spectrum portion. However, the partitioning approach reduces multiplexing gain of the overlay network as well as removes the cross-tier interference. This tradeoff has been explicitly addressed in [4], where the authors calculates the interference-limited coverage area of a co-channel femtocell base station to determine the regions for spectrum sharing and for spectrum partitioning. In [5], a system-driven criterion to determine the inner and outer regions for a hybrid spectrum usage has been studied.

However, the previous solutions allow a femtocell to operate in either shared or partitioned mode with fixed spectrum allocation. In a dynamic system environment, where users join and leave the system, shared spectrum bandwidth needs to be adjustable accordingly for efficient and flexible resource allocation. Further, we employ beamforming antenna technique that is a promising communication tool, since it can mitigate high cross-tier interference caused by the spectrum sharing.

In this paper, we develop decentralized spectrum sharing scheme with beamforming. We propose spectrum sharing algorithm that can operates in each femtocell with decentralized manner. The rest of the paper is organized as follows. The heterogeneous overlay network system and beamforming antenna models are described in Section II. We propose the dynamic spectrum sharing algorithm with decentralized approach in Section III. Performance analysis of the proposed decentralized algorithm is presented in Section IV, followed by concluding remarks in Section V.

II. SYSTEM MODEL

We consider a two-tier overlay network with macrocell and femtocells, which extends in-home coverage and provides high-speed wireless broadband services using a beamforming antenna. In 3GPP LTE [6], users (User Equipment; UE) are classified into two types based on their access to the overlaying network: MUE accesses the macrocell BS and is denoted by eNodeB (eNB), and HUE accesses to a femtocell BS and is denoted by Home eNodeB (HeNB). In network system with two femtocells, HeNB communicates with a HUE, which, however, does not interfere with a nearby MUE owing to beamforming antenna. Thus co-channel operation between macrocell and femtocell is available. On the other hand, HeNB transmits signals using omnidirectional antenna, which cause significant interference to MUE within the transmission coverage.

In our settings, the macrocell network consists of a single base station (BS) and cellular users that communicate with the BS in the cellsite of radius $R_m$. In the coverage of the macrocell BS, multiple femtocell networks have been deployed with femtocell BS’s. Each femtocell hotspot includes a uniformly distributed population of users in a circular coverage area of radius $R^f < R_m$. We assume that there is no inter-macrocell interference. Each macrocell and femtocell BS can communicate with at most one user at a time, and they may interfere with each other when they use the same frequency channel. We assume that the bandwidth spectrum is fully shared by the two tier networks to improve spectrum efficiency.
We partition the femtocells into two groups based on interference level to the macrocell user. Let us denote the femtocells over a threshold interference $I_{th}$ from the macrocell BS use a separate spectrum with the macrocell, and denote the set of such femtocells by $K_p$. The femtocells low of $I_{th}$ distance share the spectrum with the macrocell. Let $K_s$ denote the set of the femtocells that use the shared spectrum. Also let $K_t = K_s \cup K_p$.

We adopt the beamforming antenna model of [7], where signal propagation area is sectored into two parts: main lobe with gain $g_m$ and side lobe with $g_s$. The beamwidth of the main lobe is denoted by angle $\theta_m$, and that of the sidelobe is $(2\pi - \theta_m)$. The received power depends not only on the propagation distance and the path loss exponent, but also on antenna alignment angle. We assume that the beamforming antenna is directed to the target receiver such that the receiver can be included in the main lobe area and has an antenna gain $g_m$. For the nodes located in the side lobe area, the transmission will be viewed as interference, but has a lower gain $g_s$.

### III. Dynamic Spectrum Sharing

In this chapter, we investigate the process to decide which femtocell can share the spectrum with macrocell. Ideally to mitigate cross- and co-layer interference, there would be a central entity in charge of intelligently telling each cell which subchannels to use. This entity would need to collect information from the femtocells and their users, and use it to find an optimal or a good solution within a short period of time.

However, since the number and position of the femtocells are initially unknown due to the individualistic nature of the HeNBs, this approach poses some hard problems. The presence of hundreds of femtocells makes the optimization problem too complex, and latency issues arise when trying to facilitate the femtocells communication with the central subchannels broker throughout the backhaul.

A decentralized approach to mitigate cross- and co-layer interference, where each cell manages its own subchannels, is thus more suitable in this case (i.e., self-organization). In a non-cooperative solution, each femtocell would plan its subchannels so as to maximize the throughput and QoS for the nodes located in the side lobe area, the access to the shared spectrum.

Algorithm 1 shows the proposed decentralized approach. For the cross-tier interference mitigation, Algorithm 1 also judges the two constraints, signal to interference ratio (SIR) at FUE and MUE, $\gamma_f^{th}$ and $\gamma_m^{th}$ respectively. At each HeNB, $\gamma_f^{th}$ can be measured directly. The SIR constraint of MUE, $\gamma_m^{th}$ requires the individual interference from HeNBs, however we have only aggregated interference with the channel measure at MUE.

This algorithm is a decentralized scheme, thus HeNB($i$) knows only its own channel state between FUE($i$) and no other channel information at eNB and MUE. The conventional transmission procedure is preserved as possible and only modified in indispensible case. Therefore, each HeNB needs to reversely track its interference to MUE, based on MUE signal.

MUE broadcasts tone signal for channel feedback to a group of HeNBs located near MUE. Let denote this group of HeNBs as mute group, which has larger interference than a threshold $I_{mute}$. Mute group set denotes as $X = \{i | I(i) > I_{th}\}$.

Based on the receiving signal from MUE, HeNB can obtain the beam direction of MUE transmission. Each HeNB($i$) schedules FUE($i$) avoiding the MUE directed beam. Each HeNB($i$) evaluates its own interference to MUE reversely with the receiving signal from MUE at HeNB($i$), $I_{mute}(i)$ and the beamforming gain of HeNB($i$) to the MUE, $G(\theta)$. If the result is smaller than $I_{th}$, let denote these group of HeNBs as non-mute list, and then these HeNBs sends tone signal to MUE. If not, those HeNBs are included in mute list, they will move to the partitioned spectrum.

MUE measures the sum of interference from mute HeNBs, $I_{mute} = \sum_{i \in X} I(i)$. MUE calculates the inactivate probability $P_c$ with $I_{mute}$ and the limited interference $I_{req}$ that is based on the required SIR at MUE, $\gamma_{th}^{mute}$.

$$P_c = \max\{0, 1 - \frac{I_{req}}{I_{sum}}\} \quad (1)$$

MUE sends $P_c$ to eNB. Finally, each HeNB($i$) uses the partitioned bandwidth with the probability $P_c$.

Through this algorithm, the interference from HeNBs are categorized into two group, mute list and non-mute list. These grouping is executed by reverse estimation at each HeNB.
To gratify the given SIR requirement, each HeNB of non-mute list decide inactive link with the probability given by eNB broadcasting. With the law of large numbers, the random inactive method can achieve the required SIR.

IV. PERFORMANCE EVALUATION

We consider a macrocell site which contains multiple femtocell networks. There are 100 femtocell BSs, i.e. \( |K_s| = 100 \). We assume that the macrocell BS is located at \((0,0)\) and has a transmission range with radius \( R_m = 500\) m. Femtocell BSs are randomly located within the macrocell site. We set the femtocell transmission range \( R_f \) to 20 m and the path loss exponent parameter \( \alpha \) to 4. We assume that all the macrocell and femtocell BSs and UEs have a beamforming antenna with \( N_{sec} \) sectors.

Fig. 1 shows the average number of HeNBs which share the bandwidth with macrocell. As the number of beamforming sector increases, the number of severe interfering HeNBs decreases due to mitigated interference, which in turn, allows a larger number of femtocell networks to share the bandwidth spectrum with the macrocell network.

At a given beamforming sector, the centralized algorithm marked as 'Cent' has highest \( |K_s| \) with centralized sorting of HeNB’s interference which requires full channel feedback of two-tier network. The fully randomized HeNB selection for spectrum sharing is presented as 'Dist RAND'. It has less number of sharing femtocells \( |K_s| \) because of inefficient HeNBs selection. Heavy interfering HeNBs can share the spectrum with macrocell and occupy the limited interference constraints. Whereas lower interfering HeNBs cannot share the spectrum. The proposed decentralized algorithm marked as 'Dist M&C' make the higher interfering HeNBs inactive with the mute group, thus \( K_s \) of M&C algorithm approaches to the centralized one.

Fig. 2 shows the CDF of the number of sharing HeNBs \( |K_s| \) with various beamforming sector when the required SIR level at MUE is 10 dB. For the 1,000 different topologies, the Dist M&C has \( K_s \) as nearly same as the centralized one. However Dist RAND scheme has smaller \( K_s \) with large variance. Because this random cut scheme decides spectrum sharing without mute group that can exclude the severe interfere from spectrum sharing. Thus it’s performance fluctuates with large variance and the worst case performance can not be guaranteed.

V. CONCLUSION

This paper proposes a decentralized interference mitigation with beamforming antenna and hybrid spectrum usage to improve spectrum utilization for macrocell and femtocell overlaying networks. The SIR enhancement with beamforming antenna in two-tier overlay networks enables a part of spectrum to be shared across tiers for cross-tier to improve efficiency. For the spectrum sharing decision in two-tier network, the centralized scheme requires unrealistic channel information for the whole two-tier networks and induces intolerable delay with the heavy control overhead. Contrarily, the proposed decentralized decision algorithm approaches the cell capacity of centralized one with limited channel information and overhead.

REFERENCES


