On Adopting Interleave Division Multiple Access in Two-Tier Femtocell Networks: The Uplink Case

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Abstract—**A femtocell base station (FBS) is designed to cater for the demand of ever-increasing wireless data traffic, typically in the indoor environment. Among the many technical problems, interference management is particularly a challenging one for fully harvesting the high potential of femtocell networks. In this paper, we address the interference management problem with an iterative multi-user detection approach, and propose to adopt Interleave Division Multiple Access (IDMA) for the uplink of two-tier femtocell networks by exploiting the processing capability of FBS. We consider three IDMA-based schemes, namely, FBS Decode, FBS Forward, and FBS Select, and evaluate their performance with simulations. Numerical results show that the proposed schemes achieve considerable throughput gain over traditional techniques and are highly suited for the uplink of two-tier femtocell networks.**

I. INTRODUCTION

The last decade has witnessed an explosive increase in the demand of high speed wireless data transmissions. Recent studies show that more than 50% of the voice traffic and more than 70% of the data traffic are generated by indoor users [1]. Considerable research efforts from both industry and academia are being made to meet such compelling demands and provide satisfactory services to end users. Many new technologies are being developed, among which femtocell is particularly a highly promising one under this context.

A femtocell is a user installed small base station in houses or small businesses, which are connected to the service provider via broadband wireline connections. Approved users can enjoy network access through the femtocell base station (FBS) directly, rather than through the remote cellular base station (BS). With greatly reduced distances between femtocell users and wireless network infrastructure, many benefits are brought about, such as extended coverage, enhanced capacity, reduced transmit power, and prolonged battery life, among others. Compared with deploying more BS's to achieve these benefits, FBS is a much more economical choice for extending high quality services to indoor users.

To fully harvest the many envisioned benefits of femtocells, many technical problems should be addressed, among which interference management is a particularly challenging one [1]. In this paper, we consider the uplink of a two-tier femtocell network consisting of one macro base station (MBS) and multiple FBS's. An authorized user can connect to either the MBS (i.e., as a macrocell user) or a close-by FBS (i.e, as a femtocell user). For the uplink in such a two-tier femtocell network, five types of interference may exist: (i) a femtocell user's signal may be interfered by a macrocell user's signal in the vicinity; (ii) the femtocell user's signal may cause interference to the macrocell user's signal when it is close to the MBS; (iii) a femtocell user's signal in one femtocell may interfere the signals in neighboring femtocells; (iv) signals in a femtocell may interfere with each other due to multipath propagation or carrier frequency offset; (v) signals in a macrocell may interfere with each other due to multipath propagation or carrier frequency offset. The first two types of interference are classified as cross-tier interference [2], while the last three types of interference are classified as intra-tier interference.

Considerable research has been conducted for interference management in femtocell networks [2]–[7], most of which focus on cross-tier interference. In this paper, we address the interference management problem with a multi-access and iterative multi-user detection approach. In particular, we propose to adopt Interleave Division Multiple Access (IDMA) for the uplink of two-tier femtocell networks [8]. IDMA is a relatively new multi-access technology that distinguishes users by unique interleavers. With IDMA, each transmitter uses a unique interleaver to interleave its data before transmission. The mixed signals from all the transmitters are then decoded at the receiver with an iterative decoding and interference cancellation technique (see Section II-B).

With IDMA, most of the processing are conducted in the decoder, while the transmitter design can be made very simple. Therefore it is highly suited for the uplink of the two-tier femtocell network, such that the BS (with relatively higher processing capability) performs most of the computation and user devices are relieved of such burden. Compared with traditional multi-access techniques such as time division multiple access (TDMA), IDMA does not require precise synchronization of all the users [8]. Therefore the user device can be further simplified. IDMA also allows concurrent transmissions of multiple users, and does not require the use of guard times to account for different propagation delays of users. Therefore higher utilization of wireless network resources can be achieved. Compared with code division multiple access (CDMA), IDMA represents a new dimension of orthogonality that can be integrated with CDMA. For example, users can be divided into groups, each sharing a CDMA spreading sequence; users within the same group are then distinguished with unique interleavers. Thus the network capacity can be

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greatly enhanced.

In this paper, we propose to adopt IDMA for the uplink of two-tier femtocell networks, as motived by the above observations. In particular, we investigate three IDMA-based schemes: (i) Femtocell Decode, where each FBS decodes the signals locally for the users within its coverage; (ii) Femtocell Forward, where the FBS's forward the received signals to the MBS, which then decodes the signals for all users; and (iii) Femtocell Select, where the FBS performs local decoding if the number of users it serves does not exceed a threshold, and forwards received signals to the MBS otherwise. We evaluate the performance of the proposed schemes, and compare them with conventional TDMA without guard times and IDMA without the use of femtocells in simulations. Due to limit of space, we focus on the case where all the users share a common spreading sequence (since the advantage of integrating IDMA with CDMA is obvious). Our simulation study shows that the proposed IDMA-based schemes can achieve considerable throughput gains over traditional schemes and are highly suited for the uplink of two-tier femtocell networks.

The remainder of this paper is organized as follows. Section II describes the background and preliminaries. We examine adopting IDMA in femtocell networks and propose three schemes in Section III. The proposed schemes are evaluated in Section IV. We review related work in Section V. Section VI concludes the paper.

II. BACKGROUND AND PRELIMINARIES

A. Femtocell Networks

A femtocell, also called home base station, typically serves as an access point for use in home or small business. It is usually installed by wireless users for backhauling data to the service provider through a broadband gateway such as digital subscriber line (DSL), cable, et al. The most prominent feature of femtocell is that the transmission distances between wireless network infrastructure and users are greatly reduced, compared with that in traditional cellular networks. This brings about many benefits such as enhanced link quality, better signal to interference noise ratio (SINR), improved cellular capacity, and greatly reduced transmission power, among others.

Despite of these envisioned advantages, there are many technical challenges need to be addressed, such as interference management and mitigation [1], [3]. For the uplink case, TDMA or Frequency Division Multiple Access (FDMA) are conventionally used to coordinate the transmissions of users. Under the presence of multipath propagation or carrier frequency offset, however, both intra-tier and cross-tier interferences exist. Moreover, the precious time and frequency resources may not be fully exploited with TDMA or FDMA, since only one user can transmit at a time or within a frequency band, and due to the use of guard times or guard bands. Given these facts, it is natural to think about better ways for interference mitigation in femtocell networks that can make more efficient use of the wireless network resources. We consider IDMA as one of such options in this paper.

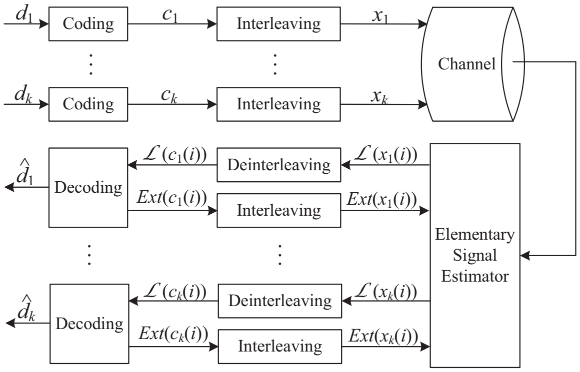


Fig. 1. The transmitter and receiver architecture of IDMA.

B. Interleave Division Multiple Access

The essence of IDMA is to distinguish signals from different users according to their unique interleavers. IDMA represents a new dimension of orthogonality, such that multiple users can transmit in the same time slot using the same frequency band. The transmitter and receiver architecture of IDMA are shown in Fig. 1 [9]. We briefly review IDMA in this section.

For the uplink case, assume that there are K users in a cell. The signals of each user, i.e., d_1, d_2, $\cdots$, d_K, are coded, interleaved and then transmitted simultaneously to the BS. In IDMA, each user employs a unique interleaver. Therefore, the users can transmit signals simultaneously, occupy the same portion of spectrum, and employ the same coding scheme, in which ways the traditional resources can be better utilized.

At the BS, the received signal is the superposition of the signals from all the users. The BS then performs iterative bit by bit decoding, as shown in Fig. 1. To simplify discussion, a synchronous BPSK system is considered. The channel is assumed to be time-invariant with only one path. However, it is shown in [8] that the decoding algorithm can be extended to more general cases, such as asynchronous system with high order constellation, or time-variant multi-path channels.

At the BS, the i-th received signal $r(i)$ is:

$$r(i) = \textstyle\sum_{k=1}^{K} h_k x_k(i) + n(i), \quad i = 1, 2, \cdots, L, \tag{1}$$

where h_k is the channel gain of the k-th user, $x_k(i)$ is the i-th transmitted signal from the k-th user, $n(i)$ is the zero mean additive white Gaussian noise with variance σ^2, and L is the coded length. It is also assumed that the channel state information is known at the BS through some channel estimation techniques. To examine the signal from the k-th user, we can rewrite (1) as:

$$r(i) = h_k x_k(i) + \xi_k(i), \quad i = 1, 2, \cdots, L. \tag{2}$$

In (2), $\xi_k(i)$ represents the interference plus noise with respect to the signal of the k-th user, which can be written as:

$$\begin{aligned} \xi(i) &= \textstyle\sum_{k'=1, k' \neq k}^{K} h_{k'} x_{k'}(i) + n(i) \\ &= r(i) - h_k x_k(i), i = 1, 2, \cdots, L. \end{aligned} \tag{3}$$

According to the Central Limit Theorem, $\xi_k(i)$ in (3) can be approximated by a Gaussian random variable when K is sufficiently large, with the following mean and variance:

$$\mathrm{E}(\xi(i)) = \mathrm{E}(r(i)) - h_k\mathrm{E}(x_k(i)), i = 1, 2, \cdots, L, \quad (4)$$

$$\mathrm{Var}(\xi(i)) = \mathrm{Var}(r(i)) - |h_k|^2\mathrm{Var}(x_k(i)), i = 1, 2, \cdots, L, \quad (5)$$

where $\mathrm{E}(r(i)) = \sum_{k=1}^{K} h_k\mathrm{E}(x_k(i))$ and $\mathrm{Var}(r(i)) = \sum_{k=1}^{K} |h_k|^2\mathrm{Var}(x_k(i)) + \sigma^2$, $i = 1, 2, \cdots, L$. The Elementary Signal Estimator in Fig. 1 computes the *Logarithm Likelihood Ratios (LLRs)* of each bit as [8]:

$$\begin{aligned} \mathcal{L}(x_k(i)) &= \log\left(\frac{p(r(i)|x_k(i) = +1)}{p(r(i)|x_k(i) = -1)}\right) \\ &= \frac{2h_k(r(i) - \mathrm{E}(\xi(i)))}{\mathrm{Var}(\xi(i))}, \text{ for all } i, k. \quad (6) \end{aligned}$$

Then the *LLRs* are deinterleaved and decoded to produce estimations $\hat{d}_k(i)$ of the original signals, for all i, k. To further mitigate the interferences between different users, the estimations $\hat{d}_k(i)$, for all i, k, are then coded, and interleaved to update the $\mathrm{E}(x_k)$ and $\mathrm{Var}(x_k)$. Based on the updated $\mathrm{E}(x_k)$ and $\mathrm{Var}(x_k)$, the Elementary Signal Estimator then recalculates the $\mathcal{L}(x_k)$, and so forth. This procedure is repeated for a prescribed number of iterations. The estimations $\hat{d}_k(i)$'s will be progressively improved and finally the BS can decode all the signals from all the users.

III. ADOPT IDMA FOR THE UPLLINK OF TWO-TIER FEMTOCELL NETWORKS

We consider the uplink of a two-tier femtocell network, where an MBS can serve users in the entire network and each FBS serves authorized users within its coverage. Using IDMA, users inside or outside the femtocells simultaneously transmit signals to the FBS or MBS, respectively, using the same frequency band. As discussed above, the greatest merit of femtocell is bringing users much closer to the wireless network infrastructure. Exploiting the computational capability of FBS, we consider the following three IDMA based schemes for the uplink of the two-tier femtocell network.

A. FBS Decode

The first scheme is that each FBS decodes the received signals locally, and then sends the decision results to the MBS. We call this scheme *FBS Decode* for short. It is demonstrated in [10] that the performance for each user depends on its Signal to Interference plus Noise Ratio (SINR) $sinr_k$, which is:

$$sinr_k = \frac{p_k|h_k|^2}{\sum_{k'=1,k'\neq k}^{K} p'_k|h'_k|^2 f(\gamma'_k) + \sigma^2}, \quad \text{for all } k, \quad (7)$$

where p_k is the transmit power of each user k, and $f(x)$ is a function representing the amount of interference canceled at each decoding iteration, which has no close form expression but can be obtained through Monte Carlo simulations [9].

Without loss of generality, assume all the users transmit at the same power. Since there are little differences in the channel gains for all the users (i.e., due to closeness to the FBS), the sum of the SINR of all the users would be quite high. That is to say, from the perspective of the system performance, this scheme is expected to perform better than the other two schemes introduced later in this section. However, since the user number served by each FBS may be large, this scheme may put a stringent requirement for the computational capability of the FBS's.

B. FBS Forward

If the computational capability of the FBS is not strong, the FBS could directly forward all the received signals to the MBS. The MBS will then decode the signals from all the users. We call this scheme *FBS Forward* for short. Since the users served by the FBS enjoy high quality channels, while cell edge users suffer from the bad ones, in the light of (7), the SINR of an FBS user is usually very high, but the SINR of an edge user is usually very low. The consequence is that although the throughput of the FBS users could be high, the overall system throughput may be degraded due to the bad performance of edge users.

C. FBS Select

This is a hybrid scheme that provides a trade-off between FBS Decode and FBS Forward. FBS Select is useful for the case when the computational capability of the FBS is not sufficiently strong. In particular, an FBS can directly forward the received signals to the MBS, if the number of users being served is greater than a predefined threshold η. Otherwise, the FBS decodes the signals locally and sends the decoded data to the MBS. We call this scheme *FBS Select* for short. The performance of this scheme is expected to lie between those of FBS Decode and FBS Forward.

It will be shown in the next section that by applying IDMA to femtocell networks, considerable throughput gains can be achieved at comparatively low cost over traditional TDMA and IDMA schemes.

IV. PERFORMANCE EVALUATION

A. Simulation Settings

Monte Carlo simulations are conducted to evaluate the performance of the proposed schemes and to verify the benefits brought about by adopting IDMA in the uplink of two-tier femtocell networks. Since power consumption is a critical factor for battery life and CO_2 emission, we focus on the performance at the low power region. Since it is a general assumption that femtocells are deployed at hotspots, 80% of the users are served by the femtocells in our simulation. For fair comparison, we simply use spreading as the channel coding scheme, and all the users share the same spreading sequence. Let the spreading sequence be $g = \{+1, -1, \cdots\}$, with length G. It follows that [8]

$$\hat{d}_k(i) = \sum_{j=1}^{G} g(j)\mathcal{L}(c_k((i-1)\times G+j)), \; i = 1, 2, \cdots, L, \quad (8)$$

$$Ext(c_k(i)) = g(i)\hat{d}_k(i) - \mathcal{L}(c_k(i)), \; i = 1, 2, \cdots, L. \quad (9)$$

The mean and variance of $x_k(i)$ can be updated as [8], [11]:

$$\mathrm{E}(x_k(i)) = \tanh\left(\frac{1}{2}Ext(x_k(i))\right), \; i = 1, 2, \cdots, L \quad (10)$$

$$\mathrm{Var}(x_k(i)) = 1 - \mathrm{E}^2(x_k(i)), \; i = 1, 2, \cdots, L. \quad (11)$$

TABLE I
SYSTEM PARAMETERS USED IN THE SIMULATIONS

Description	*Value*
Number of users	32
Number of femtocells	6
Coverage radius of MBS (normalized)	10
Coverage radius of FBS (normalized)	2
Distance between MBS and FBS (normalized)	6
Number of decoding iterations	5
FBS Select threshold η	5
Message length (bits)	128

The path gain is modeled as [12]:

$$h_k = A_k / d_k^{\alpha}, \tag{12}$$

where the A_k's are all independent and identically distributed (i.i.d.) log-normal random variables with 0 dB mean and 8 dB variance, d_k is the distance between the user and the BS it connects to (could be either the MBS or an FBS), $\alpha = 4$ for outdoor users, and $\alpha = 2$ for indoor users. When d_k approaches to 0, h_k approaches to infinity, which is impossible in practical systems. We simply let $h_k = 1$ if $d_k \leq 1$. This can be interpreted as when the user is close enough to the MBS or an FBS, the channel between them becomes perfect.

As for user locations, we first generate uniformly distributed random locations for 20% of the users, which are served by the MBS. Considering the height of the MBS and its geographic impact, these users are located outside the unit circle that is centered at the MBS. Their locations are uniformly distributed under the coverage of the MBS. Next, the remaining 80% users are randomly scattered in the femtocells. Within the coverage of each femtocell, the users are uniformly distributed. This user location generation process is performed 10,000 times in each simulation. Each point in the figures is the average of 10,000 simulation results.

The proposed schemes are implemented with MATLAB. The system parameters used in the simulations are specified in Table I. For comparison purpose, we also simulated the traditional IDMA scheme without the use of femtocells (termed IDMA w/o Femtocells), where all the users in the cell directly transmit to the MBS, and the signals are decoded at the MBS. In addition, we also simulated the conventional TDMA scheme. With TDMA, each user is assigned with an equal and nonoverlapping portion of the total time for signal transmission. We assume perfect synchronization for all the users with zero guard times, so as to obtain an upper bound on the TDMA performance.

B. Simulation Results and Discussions

We first compare the throughput of the five schemes under different signal-to-noise-ratios (SNRs). In the simulations, throughput is measured by the error-free bits received given the same time interval and same bandwidth for each scheme.

Fig. 2(a) shows the achieved throughput at different SNRs. It is obvious that by deploying femtocells, considerable throughput gains can be achieved over the IDMA w/o Femtocells scheme. It can also be observed that FBS Decode has the highest throughput performance among all the five schemes. Under FBS Forward, the channel gain differences between the FBS users and the MBS users are so large that the SINR of FBS users are extremely high while their MBS counterparts are extremely low. It can be examined that the bit error rate (BER) of high quality channel users is close to zero, while the BER of edge users is so high that the system performance is greatly affected. As expected, FBS Select's throughput performance lies in-between those of FBS Decode and FBS Forward. It is important to note that both FBS Decode and FBS Select strictly outperform TDMA with zero guard time, while the throughput of FBS Forward is close to that of TDMA with zero guard time. The relatively lower throughput of FBS Forward is due to the low quality channels of edge users.

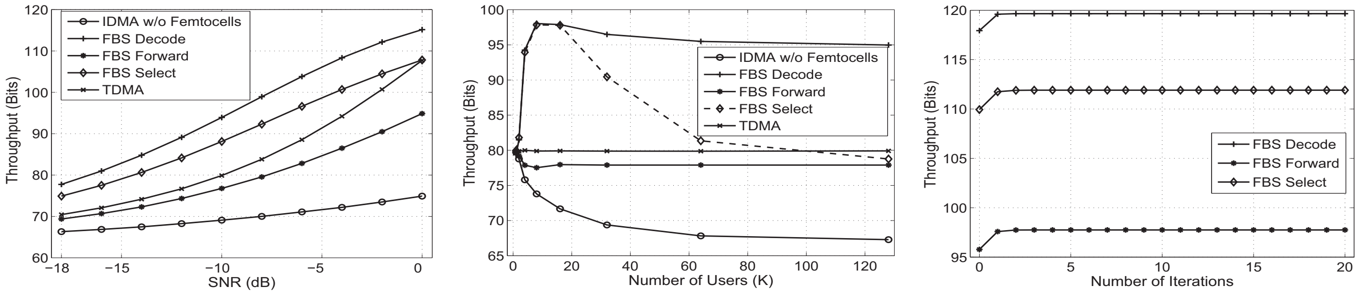
We next compare the five schemes under different numbers of users. Most of the system parameters are still the same as given in Table I, except that the SNR is set to -10 dB and the user number is varied. The simulation results are presented in Fig. 2(b). It can be observed that similar conclusions drawn from Fig. 2(a) still hold true here. FBS Decode has the best performance; the FBS Select outperforms TDMA with zero guard time when the user number is less than 90; and FBS Forward achieves a performance close to that of TDMA with zero guard time.

From Figs. 2(a) and 2(b), we conclude that if the FBS has the capability of local decoding for the signals from a certain amount of users, which is the usual case of femtocell applications, considerable throughput gains can be achieved by adopting IDMA for the uplink of femtocell networks. Even if the femtocells work in the signal forwarding mode, the performance is still close to that of TDMA with zero guard time and better than that of IDMA w/o Femtocells.

Since IDMA adopts an iterative decoding procedure (see Fig. 1), it would be interesting to investigate how fast the decoding procedure converges under the uplink two-tier femtocell network scenario. Our simulations show that the IDMA decoding algorithm can converge very fast. The simulation results are presented in Fig. 2(c) for the three IDMA-based schemes. We still follow the system parameters given in Table I, except that the SNR is fixed at 0 dB and the number of iterations is varied. It can be observed that the FBS Decode scheme converges after two iterations, FBS Forward converges after three iterations, and FBS Select converges after three iterations. Therefore, the computational complexity and processing delay incurred from the turbo iterative decoding algorithm are negligible; the throughput gains are achieved at relatively low cost.

V. RELATED WORK

Even though femtocells have the great potential of dual benefits to both network operator and users, there are many challenges to be addressed. It was pointed out in [1] that interference management is one of the key factors for the success of femtocell. Considerable research have been conducted in this problem area [2]–[7]. In [2], the authors studied the impact of the cross-tier interference on the system outage probability, analyzed the uplink capacity, and proposed an interference



(a) Throughput vs. SNR (b) Throughput vs. number of users (c) Throughput vs. number of iterations

Fig. 2. Simulation results of the three IDMA-based schemes.

avoidance strategy. To suppress the cross-tier interference below an adaptive threshold and compensate for the uplink throughput, open-loop and closed-loop interference mitigation strategies were proposed in [3]. In [4], the authors considered the cochannel interference incurred by frequency reuse, and proposed a femtocell based distributed antenna system for uplink interference cancellation. In [5], the authors proposed a coordinated user scheduling combined with transmit beamforming scheme to alleviate the inter-femtocell interference problem. We adopted successive interference cancellation for downlink multicast in two-tier femtocell networks in [7], and examined medium grain scalable videos streaming over femtocell cognitive radio networks in [6]. However, the uplink case was not fully considered in these papers.

IDMA has been shown to support multiple transmissions simultaneously using the same frequency band [8]. The quality of service (QoS) issue in IDMA-based networks was examined in [13]. An IDMA QoS architecture and an interleave division slotted-ALOHA (IDSA) are proposed and shown to be effective. Applying the large-system performance approximation and the extrinsic information transfer (EXIT) chart, Li, Wang, and Li [9] analyzed and optimized the BER of IDMA communication systems. From a game theoretical view, a decentralized power allocation algorithm for the uplink IDMA system was proposed in [10]. The optimal transmission power for the spread spectrum uplink IDMA channels was derived in [14]. In [15], a fully-analytical approach was developed to predict the rate allocation scheme of IDMA system, and a modified linear programming method is proposed to compute the best rate profile.

VI. CONCLUSIONS

In this paper, we investigated the problem of interference management in the uplink of two-tier femtocell networks. To enhance the uplink throughput performance for low power transmissions, we introduced IDMA to allow concurrent transmissions from all users and cancel the intra and cross-tier interference with iterative decoding and interference cancellation. We examined three IDMA-based schemes, namely, FBS Decode, FBS Forward, and FBS Select, for the uplink of two-tier femtocell networks that exploit the processing capability of femtocells. Simulation results demonstrated that considerable throughput gains can be achieved under FBS Decode and FBS Select over conventional TDMA and IDMA schemes at comparatively low costs.

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