A Novel Coordinated Spectrum Assignment Scheme for Densely Deployed Enterprise LTE Femtocells

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***Abstract*—With the emergence of femtocells, the complexity and heterogeneity of the mobile radio networks have been dramatically increased, which lead to more operational tasks such as self-configuration and optimization of the new distributed wireless system. The allocation of spectrum and avoidance of inter-cell interference are some of the more urgent challenges that operators have to face before femtocells become widely deployed. However, considering the small cell radius and irregular coverage area of the femto BS, the typical ICIC (Inter-Cell Interference Coordination) technologies such as FFR (Fractional Frequency Reuse) in current LTE network are not suitable for femtocells. In this paper, a novel coordinated spectrum assignment scheme is proposed for inter-femtocell interference coordination of densely deployed enterprise LTE femtocells. The proposed scheme is mainly composed of an autonomous selection process of dedicated subband for basic connectivity and a cooperated allocation process of shared subband for high data capacity. It works in a distributed and localized manner, showing a high level of scalability and feasibility.**

***Keywords*—Self-Organization, enterprise femtocells, cooperated scheduling.**

I. Introduction

One of the key drivers for next generation mobile radio systems is the reduction of cost without adverse impact on capacity and coverage. Therefore, the Local Area (LA) solution such as femtocell has become more attractive within the flat architecture of the emerging LTE mobile network. Femtocells are short-range low-cost low-power cellular radio systems which are plugged to residential DSL or cable broadband connections to provide improved indoor wireless coverage and increased throughput for mobile data services directly in buildings [1]. The femtocell delivers an indoor solution which could effectively absorb extensive local traffic from the conventional outdoor macro cells and achieve an efficient fixed mobile convergence (FMC) with the use of residential IP broadband connection behind the femto BS. The business analysis in [2][3] shows that mobile operators could benefit from lower costs and increased fixed mobile substitution, leading to higher revenues and more profitable relationships with their newfound Internet and web partners. The ABI Research [4] has released a market prediction of around 70 million femtocells installed in home or offices serving more than 150 million world-wide customers by 2012.

Practically, the operators have to solve several urgent challenges before the realistic wide deployment of femtocells [5][6]. One of the most critical issues is the co-channel interference due to the potential dense deployment of femtocell and its overlapping with macrocells. In the existing literatures, different radio resource management (RRM) strategies have been studied for femtocell deployment and coexistence with the overlapped macrocells. In [7] we have proposed a femtocell-aware spectrum arrangement scheme for co-channel interference avoidance between the macro and femto cells. The macro BS takes the knowledge of the shared frequency resource for femtocells within its coverage and proactively detects those mobile terminals having potential threat of co-channel interference with femtocells. By the efficient spectrum arranging method, the detected mobile terminals having potential threat to femtocells are allocated to the "clean" part of the spectrum which has no frequency overlapping with the femtocells. In [8], the femtocells embedded in macrocell are differentiated to inner and outer femtocells, which operate in partitioned spectrum and shared spectrum respectively. Correspondingly, the co-channel interference in the center of macrocell is avoided.

Besides the approaches of co-channel interference coordination between femtocell and macrocell, another important issue is the inter-femtocell interference considering the dense deployment of the user plug-in femto BS [9]. Unlike the conventional inter-cell interference coordination technology of normal macro cells whose locations and frequency bands are usually under professional network planning and optimization, the inter-femtocell interference coordination becomes complex due to the specific feature of user plug-in. Especially in the scenario of dense femtocell deployment which should be typical in large buildings or enterprises, the technology of smart radio resource management among femtocells becomes necessary and significant. In [10], Chandrasekhar proposes and analyzes a decentralized Frequency ALOHA method to make the neighboring femtocells access to a random subset of candidate frequency subchannels. Comparatively in [11] Lopez-Perez proposes a self-organized scheme for cooperative scheduling within the group of neighboring femtocells. The scheme makes use of either the exchanged information of subchannel assignment within femtocells or the measurement reports gathered from connected mobile users and achieves an optimal solution for subchannel assignment of neighboring femtocells. The proposed scheme depends on the knowledge exchanging of subchannel assignment for all connected uses between femtocells and the assumption limit of allocating only

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one subchannel to each user is not realistic.

This paper focuses on the decentralized solution for radio resource management and scheduling cooperation in the case of dense and irregular deployment of LTE femtocells. Differently from the conventional ICIC method of macrocells with network planning, we design a self-organized frequency assignment (SOFA) scheme which works in an autonomous way for inter-femtocell interference coordination. The proposed scheme is composed of an autonomous selection process of dedicated subband for basic connectivity and a cooperated allocation process of shared subband for high data capacity. The proposed scheme allocates the radio spectrum among the interfering femtocell systems in a distributed and localized manner, which shows a high level of scalability and feasibility.

The rest of this paper is organized as follows. In Section II, the system model is briefly described and the problem is clarified. In Section III, the novel scheme of self-organized frequency assignment for inter-femtocell interference coordination is proposed. In Section IV, the simulation results are presented and discussed. Finally, concluding remarks are drawn in Section V.

II. System Model

Generally the existing of femtocells would lead to two types of inter-cell interference: cross-layer which corresponds to the inter-cell interference between macrocell and femtocell, and co-layer which corresponds to the inter-cell interference between femtocells. For the cross-layer interference, the simplest solution is to allocate a dedicated spectrum to femtocells which is orthogonal to that of macrocells. The dedicated spectrum allocation for femtocells may reduce the overall usage efficiency of the scarce radio resource. However, for some particular operator who has planned to assign a separate spectrum for the indoor coverage (e.g. China Mobile), this would be a natural and perfect solution for the cross-layer interference avoidance.

In this paper our study concentrates on the co-layer interference solution. We consider a dense and irregular femtocell deployment scenario as shown in Fig. 1. For simplicity the interference from macrocells is not considered here. Practically if the dedicated spectrum allocation is used for femtocells, the cross-layer interference from macrocells does not exist any more. Furthermore, in the case of a spectrum sharing between macrocell and femtocell, any existing work of such a cross-layer solution including our previous study in [7] could be well complementary to the co-layer interference solution. Without loss of generality it is assumed that the femtocell network is well synchronized with an acceptable accuracy so that the inter-cell interference will occur when and only when more than one user are assigned to the same frequency resource simultaneously in surrounding femtocells.

In the OFDMA downlink system model of the dense LTE femtocells, the basic scheduling unit for mobile user in frequency domain is assumed to be subchannel which is composed of several subcarriers and then the available

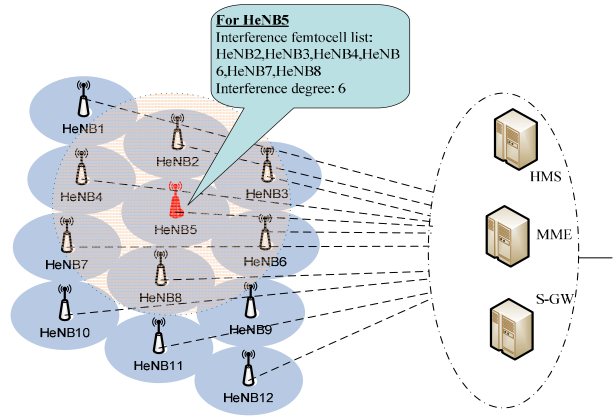

Fig. 1. Dense deployment scenario of femtocells

subchannel set is denoted by $\mathbf{N} = \{1, 2, \ldots, N\}$. Let $\mathbf{K}$ and $\mathbf{M}_k, (k \in \mathbf{K})$ denote the sets of femtocells and the active mobile users in femtocell k, respectively. Furthermore, denote by $\{a_{mn}\}, (m \in \mathbf{M}_k, n \in \mathbf{N})$ the allocation vector of subchannel n to each mobile users m in femtocell k, and by $\{p_{kn}\}, (k \in \mathbf{K}, n \in \mathbf{N})$ the power allocation for subchannel n in femtocell k. With an ideal assumption that if we could get all the channel gains between each femto BS and mobile users expressed by $\{h_{kmn}\}, (k \in \mathbf{K}, m \in \mathbf{M}_k, n \in \mathbf{N})$, the downlink subchannel and power allocation optimization problem is formulated as

$$\max_{\{a_{mn}\},\{p_{kn}\}} \sum_{k\in\mathbf{K}} \sum_{m\in\mathbf{M}_k} \sum_{n\in\mathbf{N}} \log_2\Big(1+\frac{a_{mn}p_{kn}h_{kmn}}{P_N+\sum\limits_{j\neq k} p_{jn}h_{jmn}}\Big) \quad (1)$$

$$\text{s.t.} \sum_{m\in\mathbf{M}_k} a_{mn} \leq 1, \forall n \in \mathbf{N}, k \in \mathbf{K} \quad (2)$$

$$\sum_{n\in\mathbf{N}} p_{kn} \leq P_t, \forall k \in \mathbf{K} \quad (3)$$

$$a_{mn} \in \{0,1\}, p_{kn} \geq 0, \forall k \in \mathbf{K}, m \in \mathbf{M}_k, n \in \mathbf{N} \quad (4)$$

where P_N stands for the background noise over the chunk bandwidth and P_t is the maximal transmission power limit of the femtocell.

Obviously, to have a complex channel estimation of $\{h_{kmn}\}$ for each mobile user and each femto BS on each subchannel is not realistic in practical systems. Furthermore, such a non-convex optimization problem is hard to be solved or iterated in a densely distributed femtocell system especially regarding the computing capability limit of a femto BS and the time requirement of the dynamic resource management. Therefore, here we propose a self-organized frequency assignment scheme which is based on the cooperation at femtocell level and has more practical advantages in implementation.

III. SOFA Proposal

In our work we propose a self-organized method for femtocell systems to assign the spectrum in a distributed and localized manner so that it could be adaptive to a high

TABLE I
CONTENT OF INTERFERENCE CELL LIST

Entry ID	Entry Content	
1	General cell information	physical cell identity (PCI)
		cell global identity (CGI)
		IP address
		reference signal received power (RSRP)
		interference degree
	Dedicated subband information	dedicated subband index
		usage efficiency of the dedicated subband

level of scalability. Since the number of involved femtocells may be large, to have a thorough cooperation of scheduling per user per femtocell as shown in equations (1)-(4) is not practical in reality. Therefore, our idea is to take the femtocell as the basic object and execute the spectrum assignment at the femtocell level. In this way, the sophisticated resource allocation problem is divided into two different layers and we just need to focus on the high-layer inter-cell frequency assignment, while leaving the particular multi-user scheduling down to femtocells.

A. Self-configuration of interference list and degree

In LTE, self-configuration has become a necessary feature of the femto BS. In [12], it has been agreed that the LTE femto BS needs to have a downlink (DL) receiver for autonomous detection during startup. Furthermore, the active user equipment (UE) is expected to read the broadcasted system information and do reference signal received power (RSRP) measurement reporting of all the detected surrounding femtocells in autonomous gaps or network scheduled gaps. In this way, it is intuitive for us to introduce the concepts of interference cell list and interference degree for the self-configured femtocells.

Specifically, femtocell i would consider femtocell j as an interfering cell if the detected received reference signal strength coming from femtocell j is higher than a predefined sensitivity threshold. The interference cell could be detected by autonomous searching of the femto BS itself during startup process or by the measurement reporting from the active users. The femto BS is proposed to maintain an interference cell list which contains all the surrounding femtocells that may cause non-neglectable inter-cell interference. The number of entries in the interference cell list is defined as interference degree. The interference cell list contains not only the cell identity and IP address of the interfering cells, but also the related RSRP and interference degree as shown in Table I.

The femtocell periodically updates and exchanges the interference cell list with all its interfering cells in the list and correspondingly, the femtocells in the same interfering range could cooperate with each other for dynamic frequency allocation. It is noted that the dedicated subband information part in the list is filled and updated periodically after the dedicated subband is allocated as described in subsection C.

B. Spectrum partition

Although pilot signals and control channels of the LTE system are robust enough even with frequency reuse 1 planning due to the power limited feature of femtocell systems, the overlapping of frequency resource for data channels of interfering femtocells would definitely reduce the cell capacity according to equation (1), especially in the dense deployment scenario. Therefore, the key idea of our proposal is to partition the system spectrum into several subbands and make an effective assignment to the interfering femtocells for data channel usage.

Considering an OFDMA downlink system model, we denote by W the total available bandwidth of the femtocell system and equally divide it into N subbands. Hence the frequency subband with a bandwidth of W/N becomes the basic resource unit for frequency assignment to femtocells. The subbands number N should be decided based on the total system bandwidth and the density of femtocell distribution. Generally, a larger value of N corresponds to higher flexibility of subband selection and reuse at the cost of more measurement and allocation work.

The subbands are classified into two categories: dedicated subband and shared subband. Each femtocell will be assigned a dedicated subband for basic cell connectivity and data transmission, which could at least cover any real-time service such as voice call, web browsing, etc. The assignment of dedicated subband to each femtocell offers a basic transmission pipeline with a guaranteed bandwidth of W/N. The shared subbands are residual radio resources after allocation of the dedicated subband to each femtocell. Each femtocell could dynamically occupy the shared subband with a fairness scheduling rule as defined in subsection D.

C. Autonomous selection of dedicated subband

As the system bandwidth is divided into N subbands, it provides an opportunity for the femtocell system to achieve a multi-cell gain due to the frequency selective fading feature of the indoor radio environment. Therefore, the femto BS is proposed to autonomously select one dedicated subband for basic cell connectivity. The femto BS could gather the periodic or aperiodic (on demand) measurement reports across the subbands from all its active mobile users. Since the number of active users in femtocell is quite limited and the users usually move slowly in most of the indoor scenarios, it is feasible and reasonable for each femto BS to summarize the subbands fading status of its own active users. Correspondingly, the femto BS could sort the subbands in a decreasing order depending on the summarized subband fading gains. Then the femto BS is able to select the subband which is most efficient for data transmission of all the active users.

Besides the channel fading estimation and comparison of subbands, another key feature which impacts the autonomous selection of dedicated subband is conflict avoidance with the other interfering cells. Similar to most of the network planning solution, the frequency allocation problem can be formulated in terms of graph coloring. It is well known that the coloring problem is NP-hard and therefore, a number of efficient heuristic algorithms have been developed as approximations to the optimal coloring [13]. However, since most of the existing heuristic algorithms need to collect the graph information of the total topology and begin the iteration from one initial vertex to all the others, they are not suitable for the dynamic subbands assignment of irregular femtocells with high scalability. In this paper, we develop a self-organized method for the autonomous selection of dedicated subband, which is composed of the following steps:

1) In every predefined period T_p, the dedicated subbands need to be reallocated in a sequence of decreasing interference degree. Each femto BS manages an available subband pool which is initialized as the total subband set $\mathbf{S}$ from the beginning of each period T_p. When the femto BS receives reallocation signaling messages from the surrounding nodes, it removes the subband being assigned from the available subband pool.
2) If the femto BS detects that its interfering degree is higher than any one in the interference cell list who has not allocated the dedicated subband, it should select the subband with the highest cell-summarized channel gain from the available subband pool. After the dedicated subband is decided, the femto BS broadcasts a reallocation signaling message to all the nodes in the interfering list. The reallocation message should include both the selected subband index and the usage efficiency which is defined as the ratio of current existing data throughput to the allocated bandwidth. All the femtocells who receive the reallocation message should update the dedicated subband information part in its interference cell list as shown in Table I.
3) If the femto BS detects that its interfering degree is equal with the highest ones in the interference cell list who have not allocated the dedicated subband, it should compare their reported usage efficiency in the last period. Only if the femto BS has the highest usage efficiency, it could begin subband selection and execute as step 2. If there are more than one femtocells who have both the same interfering degree and usage efficiency of the last period, the priority sequence is simply depending on the value of their physical cell identity in order to avoid unnecessary loops.
4) During the subband selection, if the available subband pool is empty, the femto BS should check through the total subband set S and select the subband according to

$$\arg\min_{i\in\mathbf{S}} e^{p_{eff}(i)}\gamma_{_{RSRP}}(i)/G_i \tag{5}$$

where G_i denotes the cell-summarized channel gain of subband i and $\gamma_{_{RSRP}}$ denotes the measured RSRP of the cell who has assigned i as the dedicated subband. Therefore, $\gamma_{_{RSRP}}/G_i$ indicates the interference impact on subband i considering power adaptation. Furthermore, $p_{eff}(i)$ denotes the usage efficiency of the cell who has assigned i as the dedicated subband. The selection strategy is trying to find the cell which has the smallest probability of spectrum usage and suffers the lowest inter-cell interference so that the impact of subband overlapping is minimized.
5) When a new femtocell joins in, all the interfering cells will send it the allocation message for the current period T_p immediately after the interference cell list is updated. If the available suband pool is not empty, the new femtocell would select the appropriate dedicated subband as step 2. Otherwise, the new femto BS would execute similarly as step 4 to find an overlapped subband with the minimized inter-cell interference impact. This dedicated subband selection is valid until the end of the current period T_p. In the next period, all the femtocells including the new one will reallocate the resource together as described above.

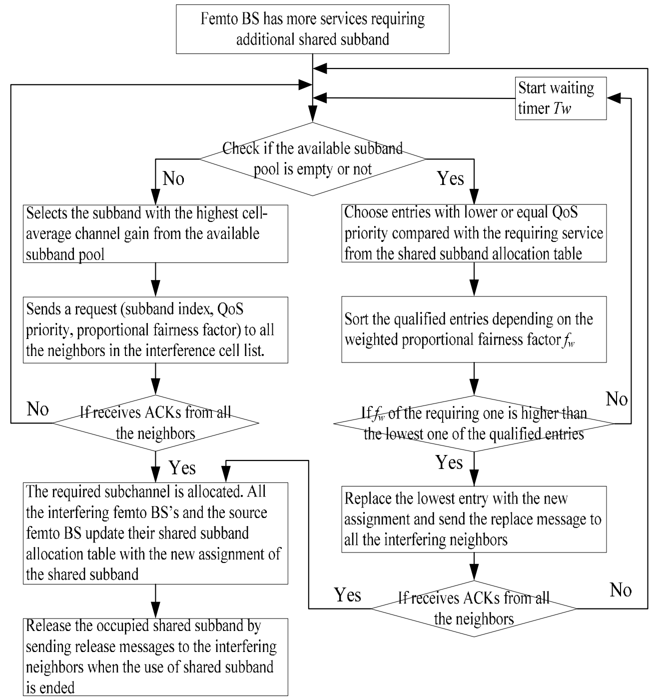

Fig. 2. Flowchart of the cooperated shared subband selection algorithm

D. Cooperated allocation of shared subbands

After the dedicated subband assignment is completed, the residual spectrum resource remained in the available subband pool would be dynamically shared among femtocells in an on-demand way. When a femto BS detects that the assigned frequency resources can not satisfy the target throughput of the Guaranteed Bit Rate (GBR) services or the downlink buffer is full for the non Guaranteed Bit Rate (non-GBR) services, it needs to request more shared subbands from the available subband pool. The flowchart of the cooperated shared subband selection algorithm is shown in Fig. 2.

When a femto BS requests more shared subbands and detects that the available subband pool is not empty, it selects the subband with the highest cell-summarized channel gain from the available subband pool and sends a request to all the neighbors in the interference cell list. The request should include the selected subband index, the QoS priority of the service Q (the higher priority corresponds to a larger value of Q) and a proportional fairness factor which is defined as

$$f = \frac{G_{i,k}(t)}{\overline{T}_k(t) + \sigma} \tag{6}$$

where $G_{i,k}(t)$ is the current cell-summarized channel gain of subband i, $\overline{T}_k(t)$ is the average obtained data throughput of femtocell k in a time window, σ is a slight positive integer to avoid the zero denominator.

If the interfering neighbors accept the request, they reply with a broadcasted acknowledgement message and the required subchannel will be allocated. After that, all the interfering femto BS's and the source femto BS should update their shared subband allocation table with the new assignment of the shared subband. The content of shared subband allocation table is shown in Table II. The entries of allocation table should be sorted in a decreasing order of QoS priority Q. The entries with the same QoS priority will be sorted in a decreasing order of a weighted proportional fairness factor f_w which is defined as

$$f_w = f \cdot \alpha^d \tag{7}$$

where $\alpha > 1$ is the weighted factor and d is the interference degree of the femtocell who occupies the shared subband. Explanatorily, since the available subband pool is different per femtocell depending on the interference degree, the femtocell with lower degree will have more choices in its available subband pool. Accordingly, the optimal way of shared subband allocation is to give higher priority to the femtocell with higher interference degree.

When a femto BS requests more shared subbands and detects that the available subband pool is empty, it should search from the bottom of the shared subband allocation table. If the QoS priority Q of the requesting service is higher than that of the lowest entry, it could replace that entry with the new assignment and send the replace message to all the interfering neighbors. If the QoS priority Q of the requesting service is equal to that of the lowest entry, the comparison of the weighted proportional fairness factor f_w is needed. If the weighted proportional fairness factor f_w of the requesting service is higher than that of the lowest entry, it could replace that entry with the new assignment and send the replace message to all the interfering neighbors. Otherwise, the femto BS will have no privilege to add any shared subband. It should start a waiting timer T_w to retry the shared subband requesting process later.

To avoid any potential conflict of simultaneous requests, the allocation of shared subband is proposed to be executed in an acknowledged way. In time between a femto BS sends out an allocation request and receives the acknowledgments, if it receives a relative shared subband request from another femtocell, the latter request is regarded as a collision and would be rejected.

TABLE II
CONTENT OF SHARED SUBBAND ALLOCATION TABLE

Entry ID	Entry Content
1	shared subband index
	cell global identity (CGI) of the femtocell who occupies the shared subband
	Q: QoS priority of the service
	f: proportional fairness factor

Finally, the femtocell should release the occupied shared subband by sending release messages to the interfering neighbors when the use of shared subband is ended. All the interfering femto BS's and the source femto BS will update their shared subband allocation table accordingly.

It is noted that since we focus on the dense deployment scenario of enterprise femtocells, the control information overhead exchanging between the femtocells are through the X2 interface based on the enterprise IP network. Therefore, the impact of the control message load at backhaul is acceptable compared with the improvement of performance.

IV. NUMERICAL RESULTS

To evaluate the performance of the proposed SOFA algorithm, we consider a dense deployment of 10MHz LTE femtocells with large scale in the simulation environment. The femtocells are assumed to be randomly distributed in an area of 5Km×5Km with a deployment grid of 50m×50m. The deployment of femto BS in each grid is decided by a random dense probability p. Practically, the interfering sensitivity threshold is assumed to be the same as the thermal noise power, which is set to -174dBm/Hz, when building the interference cell list. The modified COST 231 multi-wall model [14] is used for the indoor propagation channel and the 3GPP EPA channel model [15] is used for the multipath fading channel. As for the shadow fading, a general lognormal distribution with a standard deviation of 8 dB is used. Considering the transmission power restriction of femtocells, it is assumed that the transmission power density is limited by P_{max}/W where P_{max} denotes the maximum transmission power of femto BS (set to 10dBm in simulation) and W denotes the system bandwidth. The proposed SOFA scheme only allocates the radio resources in the level of femtocells and the well-known proportional fairness scheduler is used for user scheduling in each individual cell.

To demonstrate the advantage of giving higher priority to femtocells with higher interference degree in the autonomous dedicated subband allocation process of SOFA scheme, we compared it with a general random autonomous allocation process as the baseline. In the random allocation process, each femtocell autonomously detects the subband selection of the surrounding cells and chooses the subband with the highest cell-summarized channel gain from the remaining subbands. Since the interference degree of femtocells grows with increase of the deployment dense probability p, the available subband pool of the femto BS for dedicated subband selection might be empty, leading to a collision usage of the same subband

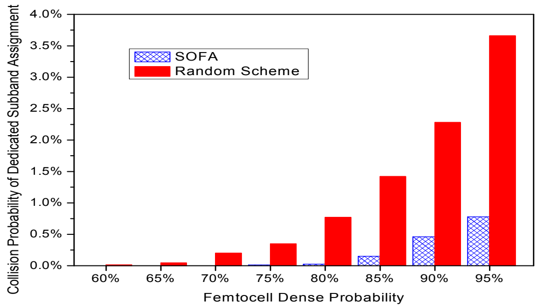

Fig. 3. Collision probability of dedicated subband assignment with increasing femtocell dense probability

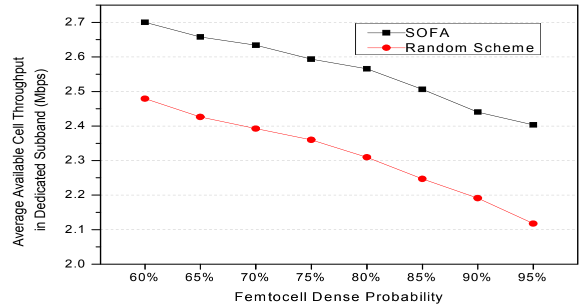

Fig. 4. Average available cell throughput achieved by dedicated subband assignment

between interfering femtocells. Fig. 3 presents the collision probability of dedicated subband assignment for SOFA and the random scheme, respectively. The results show that with the interference degree oriented autonomous selection, the SOFA scheme could approach a much lower collision probability compared with the random scheme. Correspondingly, the average available cell throughput depending on the autonomous dedicated subband assignment of SOFA is improved compared with that of the random scheme as shown in Fig. 4, where the data traffic at each femtocell is assumed to be saturated.

To evaluate the performance of the cooperated shared subband allocation scheme, heavy traffic scenarios are simulated for the densely deployed femtocells. The service arrival at each femtocell is assumed to be a poisson process with rate λ and the service duration time is assumed to be exponential distribution with the mean of 1 second. The QoS priority Q of the arriving service is randomly determined by 1 or 2 which corresponds to non-GBR and GBR services. Within a simulation time window a satisfactory rate R_s is defined to reflect the overall average rate of satisfied services number to total arrived service number, being weighted by QoS priority:

$$R_s = \Big(\sum_{n=1}^{N_{cell}} \frac{\sum_{i=1}^{N^n_{satisfied}} Q_i}{\sum_{j=1}^{N^n_{arrived}} Q_j}\Big)/N_{cell} \tag{8}$$

TABLE III
SATISFACTORY RATE (10M SYSTEM BANDWIDTH, FEMTOCELL DENSE PROBABILITY $p = 0.8$)

Scenario	R_s (SOFA)	R_S (random)	Increase ratio
identical service arrival rate $\lambda = 4$/s for each femtocell	0.8322	0.6898	20.64%
service arrival rate $\lambda \sim$ U$(0, 8]$/s for each femtocell	0.7211	0.4989	44.53%

Table III shows the overall satisfactory rate R_s evaluated in both cases of identical and uniform distributed assumption for service arrival rate of each femtocell. Since the cooperated allocation of the shared subbands has taken into account of the QoS, fairness at cell level and the interference degree, the proposed self-organized scheme is observed to increase considerably the satisfaction probability compared with the random strategy.

V. CONCLUSION

Femtocell is an attractive proposition for mobile consumers and operators alike. With the trend towards in-building femtocell deployment, the wide distribution of cooperated femtocells as enterprise solution would be an important and interesting business case. This paper presented a self-organized frequency assignment (SOFA) scheme to allocate the radio spectrum among the interfering femtocell systems in a distributed and localized manner, which shows a high level of scalability and feasibility. With the proposed scheme, the densely deployed femtocells could operate in an "interference free" state, in which the total system performance is optimized and the fairness among femtocells is guaranteed. The advantage of the proposed scheme has been analyzed and validated by simulations.

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