MobiCom 2009 Poster: DANCE: A Game-Theoretical Femtocell Channel Exchange Mechanism

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The femtocell system is an efficient solution to increase the wireless systems coverage. However, femtocells may experience spatially diverse interferences. A proper exchange on the channels between femtocells can improve the transmission experience. We proposed game-theoretical DANCE *mechanism to derive the optimal allocation in the femtocell channel allocation problem. The simulation results showed that DANCE mechanism can enhance the channel allocation efficiency significantly.*

I. Introduction

Increasing the system capacity of a wireless link is one of the most important issues nowadays. For wireless technologies using high-frequency spectrum such as 3G, WiMAX, LTE, their signals degrade significantly in indoor environments. Femtocells are introduced to efficiently solve the capacity problem [1]. A femtocell base station (BS) is a BS with low transmitting power connecting to the service provider's network via local broadband internet access. It incorporates the functionality of a typical BS but extends it to allow a self contained deployment [2]. Note that femtocell BSs typically operate in the licensed spectrum and may use the same frequency as macrocells. Furthermore, their coverage may overlap with the macrocell. Thus, the resource transaction problem within femtocells and macrocell becomes an important issue.

I.A. Inter-Femtocell Channel Exchange

We now consider a overlay macrocell-femtocell system with a single macrocell BS and multiple femtocells. Each femtocell possesses a channel assigned by the macrocell BS, and there is no inter-channel interference between channels. Femtocells at different locations of the macrocell will have different preferences for the channels due to spatially diverse channel qualities, which are influenced by nearby cells and noise. Chances are that some femtocells would experience performance improvement if they exchange their channels. An illustration of the femtocell system is shown in Fig. 1. Three femtocells experience spatially diverse interference. Femtocell 2 and 3 experience great interference in channel 4 and 2 respectively. A simple exchange of the allocated channels between femtocell 2 and 3 can improve the transmission experience of both users in these femtocells. Our goal

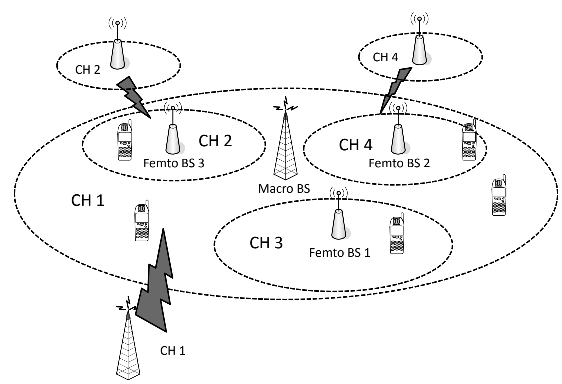

Figure 1: A Femtocell System with Interference

is to design a self-organized mechanism that femtocells exchange their channels according to the quality of channels experienced by themselves.

Guvenc *etal.* [3] provided a technique for frequency assignment for femtocell. They introduced the concept of interference-limited coverage area (ILCA) for analysis. Sundaresan and Rangarajan [4] provided location-based resource management algorithms for the purpose of leveraging maximal spatial reuse in OFDMA-based femtocells. These works mostly focus on the centralized optimization mechanism controlled by macrocell base station. Our work focus on the self-organized and simple channel exchange process based on each femtocell's preference for channels. We formulate this problem with game theory. A graph-based DANCE mechanism is proposed for oeverlay macrocell-femtocell system.

II. Problem Formulation

We define $N = \{1, 2, ..., n\}$ be the set of femtocells and $C = \{1, 2, ..., c\}$ be the set of channels available in the overlay macrocell-femtocell system, with $c \geq n$. The preference toward the channels of a femtocell are defined with the qualities of channels it experiences. The higher the quality of a channel is, the more preferred by the femtocell. The preference ordering, which we assume to be strict, of a femtocell can be written as a permutation of the channels. The preference ordering of femtocell i is represented as a relation $\succ_i$. $j \succ_i k$ means channel j is more preferred than channel k. The set of all preference of a femtocell is P. We write $\succ = (\succ_1, ..., \succ_n) \in P^n$ as the preference profile of femtocells.

We define an allocation to be $a = (a_1, a_2, ..., a_n)$ such that $a_i \in C \wedge i \neq j \Rightarrow a_i \neq a_j$, where a_i is the channel assigned to femtocell i in this allocation. The set of all allocations is denoted as A. Initially, each femtocell possesses a channel. We have an allocation $a^0 = (a^0_1, a^0_2, ..., a^0_n)$. Our goal is to find a $a' \in A$ according to $\succ$ through channel exchange process.

II.A. Game Theoretic Model

Femtocells in the system try to exchange channels for better transmission experience. Their only concern is their own transmission experience. A game-theoretical model is suitable for formulating this channel allocation problem. Game theory is used to model and analyze interactive decision processes. Players are assumed to choose their actions to maximize their utility. In the channel allocation problem, femtocells are the players. Their actions are the preferences they report, and their utility is the ranking of the channel.

We should note that the preference ordering $\succ_i$ of a femtocell is private information. Femtocells may choose to misreport their preferences in order to cheat in the game in exchange for a better channel. Cheating in the game will result in inefficient channel allocation. Our objective is to propose a mechanism that can encourage femtocells to report their preferences for the channels truthfully.

III. Simple Channel Allocation

In a resource allocation problem, the existence of the *core* allocation is an important characteristics for stability concerns. We called a subset of N a *block coalition* if members in the subset can receive more preferred channels by exchanging among themselves. An allocation that is not blocked by any subset of N is a core allocation. The searching of core allocation is important because it promises a stable allocation. In our problem, we first discuss a simple case that all channels are allocated to femtocells. In this case, the channel allocation problem can be formulated into the house allocation problem [5]. It has been proved that the house allocation problem has a unique core allocation, which can be derived by the *Top Trading Cycle Algorithm* (TTCA) [5][6]. We state it as Theorem 1.

Theorem 1 *The allocation returned by TTCA is the unique core allocation.*

The initial step of TTCA for the channel allocation problem is constructing a directed graph with the femtocells N as vertices. Each femtocell points out a directed edge toward the femtocell owning its most preferred channel. We perform exchanges on the non-overlapping directed cycles formed by the edges. All femtocells in the cycles receive the channels to which their edges point. After the exchanges, we eliminate the femtocells from the femtocell list and remove the preferences regarding the femtocells from the preference profile. Then, we start over again constructing a graph until all femtocells are removed.

Based on TTCA, we can construct a TTCA mechanism for the channel allocation problem. It has been shown that TTCA mechanism is strategy-proof [6]. We state it as Theorem 2.

Theorem 2 *The TTCA mechanism is strategy-proof.*

IV. DANCE Mechanism

The TTCA mechanism is well-suited for the channel allocation problem when all channels are occupied by the femtocells. However, in the general cases the macrocell may keep some channels to serve those users not covered by the femtocells. In this case, we cannot apply the TTCA mechanism directly into the channel allocation problem since the channels kept by the macrocell will have no outgoing edges and cannot be allocated to any femtocells.

For the general channel allocation problem, we proposed *Dummy-Assisted Negotiated Channel Exchange (DANCE)* mechanism with the idea of putting dummies $d_i, i = 1 \sim c - n$ into the system. The macrocell BS internally assigns each unallocated channel to a dummy and apply the dummies preferences for the channels $\succ^d_i$ with the dummy preference function F^d_i. Now all channels are allocated, and TTCA can be applied to find the core allocation. In DANCE mechanism, the macrocell BS joins the channel allocation game by controlling the preference of dummies. The issue in DANCE mechanism is how to select the preference ordering of each dummy without losing the characteristics from Theorem 1 and 2. Theorem 3 gives us a hint on it.

Theorem 3 *DANCE is strategy-proof with a unique core allocation if $\succ_i^d$ are strict and not related to femtocells' preferences, that is,*

$$\succ_i^d = F_i^d(\succ^u, Y) = F_i^d(\succ^{u'}, Y) = F_i^d(Y).$$

Proof If the preferences of dummies are not related to the preferences of femtocells $\succ^u$, femtocells cannot misreport their preferences with $\succ^{u'}$ to modify the preferences of dummies. That is, the dummies can be treated as real independent players in the channel allocation problem. So we can directly apply Theorem 1 and Theorem 2 on DANCE mechanism. Theorem 1 ensures a unique core allocation, while Theorem 2 promises the strategy-proofness.

IV.A. Randomized Preference

We first proposed a simple mechanism for non-prioritized femtocells: Randomized Preference Ordering (RPO). The macrocell BS randomly generates preference orderings for channels and attaches them to the dummies. We defined the set of all preferences for channel set C as $P(C)$ and R(C) as the random function. The dummy preference function is

$$F_i^d(Y) = F_i^d(P(C)) = R(P(C)).$$

Because the preferences of dummies is not related to the preferences of femtocells, Theorem 3 promises the strategy-proofness and the unique core allocation. However, DANCE-RPO could lead to inefficient channel allocation because femtocells may not receive the preferred channel when a dummy choose the channel as its preferred channel. To increase exchanging efficiency, we proposed the Enhanced Randomized Preference Ordering (ERPO). Dummies randomly rank channels allocated to N as their first to nth preferred channels. We define the channels allocated to N as $c(N)$, and the dummy preference function is

$$F_i^d(c(N), C) = \{R(P(c(N))) \succ_i^d R(P(C \backslash c(N)))\}.$$

V. Simulation Results

We evaluate the efficiency of DANCE mechanism through computer simulations. We setup 5 femtocells and 10 channels and randomly generate the preference orderings of femtocells among the channels. We apply DANCE mechanism with Randomized PO (RPO) and Enhanced RPO (ERPO). For comparison, we also simulate TTCA mechanism and a mechanism that femtocells are randomly assigned with a channel.

Table 1: Simulation Results

Femtocell	1	2	3	4	5	AVG
Random	5.47	5.50	5.47	5.49	5.47	5.48
TTCA	3.16	3.20	3.24	3.13	3.22	3.19
RPO	2.23	2.19	2.25	2.22	2.22	2.22
ERPO	1.54	1.53	1.53	1.55	1.53	1.54

Table 1 shows the simulation results. DANCE mechanisms outperforms randomly assign channels mechanism and TTCA mechanism significantly with higher average channel ranking. We also observe that every femtocell gets best ranking on average in ERPO.

VI. Conclusion

We considered the channel allocation problem through channel exchange process in a overlay macrocell-femtocell system for femtocells with channel preferences. The existence of the unique optimal allocation of the channel allocation problem has been proved. We proposed DANCE mechanism for a general femtocell channel allocation problem. The simulation results showed that DANCE mechanism can enhance the channel allocation efficiency significantly.

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