Inter-cell Interference and Frequency Reuse in Heterogeneous Networks

†Thant Zin Oo, ‡Choong Seon Hong
Department of Computer Engineering, Kyung Hee University, Yongin, 446-701 Korea
{†tzoo, ‡cshong }@khu.ac.kr

Abstract

In heterogeneous networks, small cell base stations are deployed overlaid on the existing macro cells to offload network traffic, optimize coverage and improve the overall network capacity. Due to the disparity in cell sizes, the existing intra-tier inter-cell interference management (among macro cells) mechanisms will not be effective for the inter-tier inter-cell interference management (between macro and small cells). As a result, the full potential of frequency reuse gained by deploying small cells will be diminished. We propose a mechanism to analyze the inter-tier interference in terms of frequency reusability.

1. Introduction

The vision for fifth generation (5G) wireless network is to increase capacity by three orders of magnitude, i.e. 1000-fold gains in capacity. One of the viable solution is the deployment of dense small cell base stations (SCBSs) overlaid on the existing macro cells as a heterogeneous network (HetNet). In HetNets, SCBSs offload network traffic, optimize coverage and improve the overall network capacity.

The first challenge in HetNet is interference management. HetNet introduces the disparity in cell sizes into an already complex environment. Due to different capabilities of base stations (BSs), the existing intra-tier inter-cell interference management (IM) (among macro cells) mechanisms will not be effective for the inter-tier inter-cell IM (between macro and small cells). As a result, the full potential of frequency reuse gained by deploying small cells will be diminished.

The second issue is the frequency reuse. According to Shannon-Hartley theorem, $C = W\log_2(1+SINR)$, channel capacity, C, is directly proportional to the available frequency bandwidth, W and base two logarithmic function of signal-to-interference-plus-noise ratio, $SINR$. Smaller cell size translates to more cells being able to use the same frequencies and having overall system wide capacity increase. However, HetNet presents a unique challenge with different cell sizes and different reuse patterns for them.

There are many existing works on the topics of inter-cell IM [1] [2] [3] and frequency reuse [4] [5] [6] [7]. At present, inter-cell interference coordination (ICIC) [1] and enhanced ICIC (eICIC) [2] are currently deployed in 3G and 4G wireless networks. ICIC [1] is a scheduling strategy in time and frequency domains that restricts usage of parts of bandwidth to limit inter-cell interference. However, ICIC was introduced in 3GPP release 8 and cannot handle HetNets. Thus, eICIC [2] was introduced in which Macro BSs remain silent for some sub-frames, named almost blank sub-frames (ABS). SCBSs can transmit during ABS. Frequency reuse (FR) is closely related to the IM and cannot be separated. To mitigate interference, a traditional frequency reuse or more enhanced schemes such as fractional frequency reuse (FFR) [4] and its variations, Partial Frequency Reuse (PFR) [5], multi-pattern reuse [6], can be utilized. Authors of [7] proposed Reference based Interference Management (REFIM) for IM and FR. These works show that we can still improve the IM and FR of cellular networks.

Table 1. Cell types and their order of magnitude

Cell type	Typical cell size	Cell radius (m)	Coverage area (m²)	# of UE, (λ UE/m²)	# BS for 100 km²
Macro	$1-30km$	10^4	$10^8\pi$	$10^8\pi\lambda$	1
Micro	$200m-2km$	10^3	$10^6\pi$	$10^6\pi\lambda$	10^2
Pico	$4-200m$	10^2	$10^4\pi$	$10^4\pi\lambda$	10^4
Femto	$10m$	10	$10^2\pi$	$10^2\pi\lambda$	10^6

For future dense HetNets, the existing IMs are not sufficient to achieve 5G's vision. They were designed for two-tier HetNets, e.g. eICIC was designed for macro-pico cells. Future dense HetNets will consist of n-tier cells in which macro BS will provide signaling and control services and SCBSs will perform the actual data communications. Shannon-Hartley theorem clearly shows the capacity gain for smaller cell sizes. However, dense HetNets introduce more complexity. Table 1 displays cell types and their orders of magnitude for coverage area and number of users that each can serve. From Table 1, we can see that if cell radius is decreased by one order of magnitude, the number of users inside the cell coverage decreases by two orders of magnitude. Furthermore, from the number of SCBSs will be very large leading to huge overhead for control and signaling messages for centralized control mechanisms. As a result, system design optimization shifts from centralized legacy power control convex optimization problems to distributed association problems which are combinatorial.

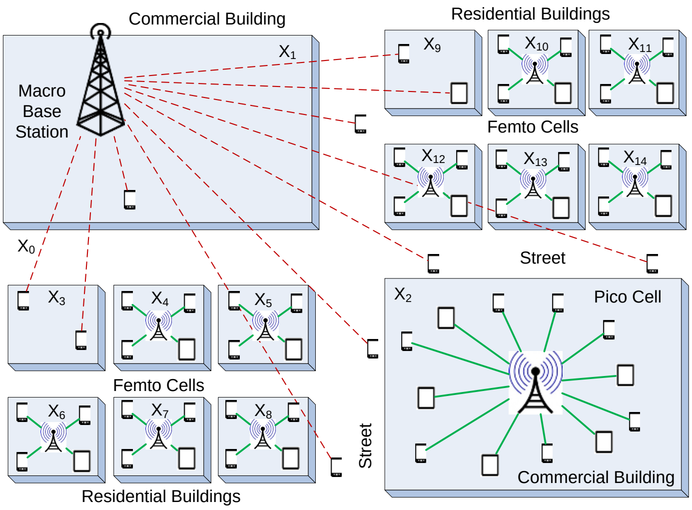

Fig.(1) Dense three-tier HetNet in an urban environment

2. System Model

Firstly, we will model the user demand as in [8]. As displayed in Fig.(1), a region, $X \subset \mathbb{R}^2$, which is X is divided into a set of discrete finite mutually exclusive and collectively exhaustive, sub-regions, $X = X_0 \cup X_1 \dots \cup X_n$. We assume that the user requests arrive in a sub-region X_i following a Poisson Point Process (PPP) with arrival rate per unit area λ_i and the requested file size is independently distributed with mean $1/\mu_i$. Thus, traffic load density can be defined by $\gamma_i := \lambda_i/\mu_i$. If each sub-region X_i has an area of a_i, the number of users can be given by $N_i = \lambda_i a_i$. We can consider each building as a sub-region and X_0 as outdoors. Some buildings will have no SCBS and the users will be served by the MBS. For example, in Fig.(1), $X_0 \cup X_3 \cup X_9$ is served by the MBS.

Secondly, we will model the available resources of the system similar to [9]. Let the set of BS $B = B_{macro} \cup B_{pico} \cup B_{femto}$ serves the region X and $|B| = K$. The system has a set of orthogonal subcarriers $S = \{S_1, S_2, \dots, S_M\}$. The transmission rate from BS k to user equipment (UE) v on a subcarrier s is given by Shannon capacity as:

$$c_{s,k,v} = w \log_2(1 + SINR_{s,k,v}) \qquad (1)$$

where $c_{s,k,v}$ is the capacity, w is the fixed bandwidth of a subcarrier (for LTE downlink OFDMA, $w = 15kHz$). $SINR_{s,k,v}$ is the received signal-to-interference-plus-noise ratio between BS k and UE v and is given by:

$$SINR_{s,k,v} = \frac{p_{s,k,v}\, g_{s,k,v}}{\sigma^2 + I_{s,k,v}} \qquad (2)$$

where $p_{s,k,v}$ denotes the transmission power of BS k, and $g_{s,k,v}$ denotes the channel gain from BS k to UE v on subcarrier s, including path loss, shadowing and other factors. σ^2 denotes noise power and $I_{s,k,v}$ denotes the interference at UE v on subcarrier s is given by, $I_{s,k,v} := \sum_j p_{s,j,v}\, g_{s,j,v}$, $j \neq k$. We consider discrete power levels, i.e. $Q_k = \{q_k^{min}, \dots, q_k^{max}\}$. Clearly, MBSs have higher transmission power than SCBS. For subcarrier allocation, we define a binary variable $\boldsymbol{\alpha}$ as a 3 dimension matrix for assignment where the element $\alpha_{s,k,u} = \{0,1\}$.

3. Problem Formulation

We can formulate the maximum frequency reuse and minimum interference problem into a power control problem similar to formulation in [10] as follows:

$$\text{minimize:} \quad \sum_{k=1}^{K} \sum_{s=1}^{M} \sum_{v=1}^{N_k} \alpha_{s,k,v}\, p_{s,k,v} \qquad (3)$$

$$\text{subject to:} \quad \sum_{s=1}^{M} \sum_{v=1}^{N_k} \alpha_{s,k,v}\, c_{s,k,v} \geq \gamma_k a_k, \forall k \in B, \qquad (4)$$

$$\sum_{s=1}^{M} \alpha_{s,k,v} \geq 1, \forall v \in U_k, \forall k \in B, \qquad (5)$$

$$\sum_{k=1}^{K} \alpha_{s,k,v} \leq 1, \forall v \in U_k, \forall s \in S, \qquad (6)$$

The objective (3) denotes the total transmission power of the system. The constraint (4) means that each BS capacity must satisfy its user demand (load). Constraint (5) describes that a BS must allocate at least one subcarrier to its UEs. Constraint (6) denotes that a UE can be associated with at most one BS. From constraint (4), we can see that the problem is non-convex. This is a mixed integer programming problem (MIP) which is NP-hard.

4. Game Theoretic Model

Although centralized solutions can provide an optimal solution to the problem, the computational cost and implementation complexity is very high. Moreover, for future dense HetNets, the control message overhead will be very huge. We propose a distributed solution based on a game theoretic model in [9] in which the system can self-organize itself.

For each BS k, total number of possible transmit configurations is $L_k = |S||Q_k|$, and their set is:

$$Z_k = Q_k \times \mathbb{I}_s = \left\{Z_k^{(1)}, \dots, Z_k^{(L_k)}\right\} \qquad (7)$$

where $\mathbb{I}_s$ is the $|S| \times |S|$ identity matrix. Let Z be the finite set of all possible configurations (actions) of the overall system, $Z = Z_1 \times \dots \times Z_K$. Then the set of all probability distributions over the elements of Z is denoted by $\Delta(Z)$. The utility (outcome) function is defined as:

$$u_k(z_k, \boldsymbol{z}_{-k}) = -\sum_{k=1}^{K}\sum_{s=1}^{M}\sum_{v=1}^{N_k} \alpha_{s,k,v}\, p_{s,k,v} \quad (8)$$

where $\boldsymbol{z}_{-k}$ represents configurations of other BSs except k. The negative sign is added to the objective function (3) to transform the problem into a maximization problem. Then, the maximum frequency reuse and minimum interference problem can be modeled as the following game:

$$G = (B, \Delta(Z_k), u_k) \quad (9)$$

We can refer to elements of $\Delta(Z_k)$, the set of probability distributions, as strategies. A strategy is denoted by the vector $\theta_k = \left(\vartheta_k^{(1)}, \dots, \vartheta_k^{(L_k)}\right) \in \Delta(Z_k)$.

Each BS k chooses its configuration from the finite set Z_k following its strategy θ_k at every time slot, i.e. each BS k plays action $Z_k^{(z)}$ with probability $\vartheta_k^{(z)}$. Then, the strategy $\vartheta_k^{(z)}$ is updated as follows:

$$\vartheta_k^{(z)} = \frac{\exp\left(\beta\, u_k(z_k, \boldsymbol{z}_{-k})\right)}{\sum_{z_k' \in Z_K} \exp\left(\beta\, u_k(z_k', \boldsymbol{z}_{-k})\right)} \quad (10)$$

where β is temperature parameter. When $\beta \to 0$, each action will be chosen with equal probability, i.e. $\Delta(Z_k)$ will become a uniform distribution. When $\beta \to \infty$, the action with the most reward, i.e. highest utility, will be chosen with higher probability. (10) is obtained from the log-sum-exp approximation of the maximization of the utility function. Its derivation is given in [11]. (10) is also known as the Gibbs sampling equation. Every BS k will choose its actions according to its strategy and update its strategy. This process will continue until it converges to an equilibrium. In [9], authors proved that at least one Logit equilibrium exists for this method.

This mechanism can be implemented cooperatively or non-cooperatively. If there is cooperation between BSs, the algorithm will converge very quickly. SCBSs can report to MBS which, in turn, broadcasts collected system information to all SCBSs. However, the reporting SCBSs configuration can be a significant overhead. Due to disparity in transmission power of BSs, the interference relation between cells is not symmetric. MBS is the major interferer to all SCBSs. Thus, the information on configuration of MBS is necessary for quick convergence. However, SCBSs effect only local UEs. Thus, only a limited exchange of BS configuration information is required locally.

5. Conclusion

In this paper, we discussed about dense HetNets and their orders of magnitude, the effect of inter-tier inter-cell interference and frequency reuse. Then we formulate maximum frequency reuse and minimum interference problem as a power control problem. This problem is non-convex and NP-hard. We then transform this problem into game theoretic model to solve. We then provide a solution that converges to an equilibrium.

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