*ICIC Express Letters*
Volume **11**, Number **9**, September **2017**

ICIC International ©2017 ISSN 1881-803X
pp. 1367–1374

# PARTIAL INTER-CELL INTERFERENCE COORDINATION BASED ON OFDMA SYSTEMS

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Received March 2017; accepted June 2017

Abstract. *This paper proposes a partial inter-cell interference coordination (ICIC) scheme to mitigate inter-cell interference in OFDMA systems, where the position of base stations is modeled as a Poisson point process (PPP). In partial ICIC, users in each cell are split into two groups according to the co-channel threshold. Different from existing work, the co-channel threshold is derived based on the stochastic geometry theory rather than a numerical root-finding. The users, who have a distance lower than the co-channel threshold from its home BS, are called as 1-reuse users. For these users, 1-reuse scheme is employed, i.e., frequency reuse factor is 1. Correspondingly, the rest of users are called as fractional reuse users. For these users, by coordinating over $k$ number of neighboring BSs, a reuse factor of $k$ is employed. Here, for the specific user, $k$ is determined by its coordination region, which is calculated according to parameters including the distance to its home BS, downlink transmission power, schedule policy and density of interferers. Simulation results show that a significant improvement in cell capacity and cell-edge user capacity is achievable.*

**Keywords:** Stochastic geometry theory, Poisson point process, Inter-cell interference coordination (ICIC)

1. **Introduction.** Stochastic geometry model [1,2], a tractable and realistic model for cellular networks, attracts great interests recently. In this model, cellular base stations (BSs) are mostly distributed as a Poisson point process (PPP). However, because of randomly distributed interferers in the network, cell-edge users who are far away form their home BSs may suffer from serious inter-cell interference (ICI) in OFDMA based systems. Inter-cell interference management is therefore more important to improve cell-edge user performances.

Inter-cell interference coordination (ICIC) [3-9] has been shown to be a powerful tool for dealing with ICI by assigning different radio resources to users from different cells. There are typically two kinds of ICIC strategies: BS-centric coordination schemes and user-centric coordination schemes. For BS-centric coordination schemes, the most relevant example is frequency reuse schemes [3-5]. Users in each cell are split into several groups, and the system determines coordinating BSs to suppress interference for each group in a pre-designed way. Additionally, resource allocating pattern in these schemes is also pre-designed and does not account for users' deployment. BS-centric ICIC can achieve good tradeoff between the spectral efficiency and cell-edge users' performances with low complexity and small signaling overhead in hexagonal-grid model. However, it is suboptimal and may be misleading since the pre-designed coordination pattern cannot cope well with the dynamics of users and diversification of BSs. Another kind of ICIC is user-centric coordination schemes [6-9] which determine coordinating BSs for each user and assign radio resources dynamically according to different network characteristics. However, a major drawback of these schemes is dynamic accounting for coordinating BSs and available radio resources of users in the network, which will bring a heavy computational burden. Furthermore, most of them do not include the treatment of stochastic geometry models and density of interferers which are necessary for the system design. Therefore, some efficient ICIC strategies are requested for random wireless networks. In this paper, we exploit a partial ICIC scheme combining the benefits of both BS-centric ICIC and user-centric ICIC to enhance spectral efficiency while mitigating ICI.

Different from the publishing papers [3-9], we split users into two groups based on the co-channel threshold. One group is called as 1-reuse users; the other group is called as fractional reuse users. Here, the co-channel threshold is a nonlinear function related to parameters including the distance between the user and its home BS, downlink transmission power, density of interferers, and coverage requirement. For 1-reuse users, single-BS serving and 1-reuse scheme is employed, i.e., frequency reuse factor is 1. For fractional reuse users, by selecting $k$ number of coordinating BSs from their coordination regions, only fraction frequency reuse can be used. With $k$-BSs coordination, user data is transmitted only from one BS, while control information is exchanged between the home BS and the $k$-1 strongest interference BSs. Therefore, it can detect and mitigate ICI effectively by this way; and it reduces the computational complexity and improves spectral efficiency.

The remainder of this paper is organized as follows: system model and partial ICIC are introduced in Section 2; derivation of the co-channel threshold and the coordination region is provided in Section 3; simulation results are given in Section 4; Section 5 concludes the paper.

2. **System Model and Partial ICIC.** We model the position of BSs as a PPP with intensity $\lambda$ and consider a typical mobile user at a distance $r$ who is served by its closest base station called home BS, as shown in Figure 1. We focus on the downlink transmission and assume that each BS uses the same transmit power.

In what follows, $r$ denotes the distance between the user and its home BS; $\gamma$ is the co-channel threshold which will be derived in Section 3; the shadow areas represent co-channel regions whose radius is $\gamma$. Partial ICIC is described as follows.

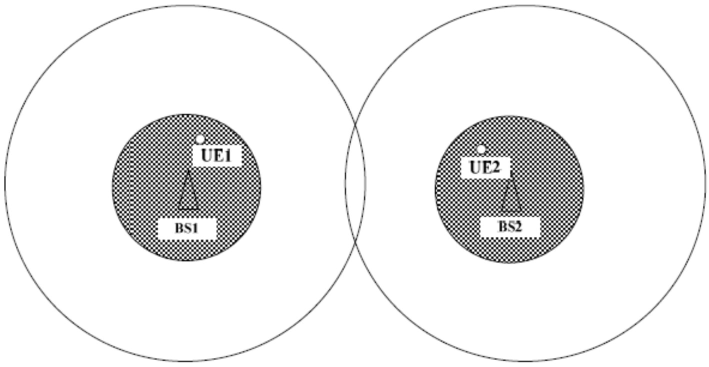
i) For users with $r \leq \gamma$ (inner-cell users), 1-reuse scheme is employed. For example, in Figure 1(a), UE1, who is inside of the shadow area of its home BS denoted as BS1, can share the same frequency band with UE2 who is inside of the shadow area of BS2.

ii) For users with $r > \gamma$ (fractional reuse users or cell-edge users), $k$-BSs coordination policy is employed. That is to say, these users employ a reuse factor of $k$. Here, for a specific user, $k(\geq 1)$ is determined by the number of BSs included in the coordination region of the user. For example, the coordination region of UE1 in Figure 1(b), includes BS1 and BS2. Therefore, UE1 employs a reuse factor of 2.

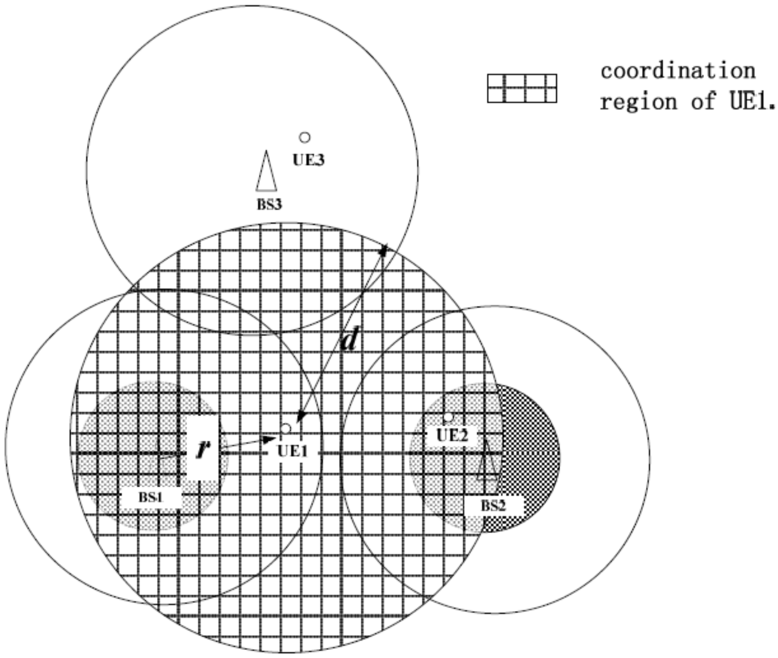
Here, $d$ is a dynamic threshold which is determined by $r$ (the distance between the user and its home BS), downlink transmission power, the density of BSs, and the SINR threshold.

According to the above mentioned partial ICIC rules, the available frequency band set of a specific user, denoted as UE0, is $\Omega\backslash S$. Here, we use $\Omega$ to denote the set of the whole available frequency band in the network. We use $S$ to denote the set of the frequency band occupied by BSs which are inside of the coordination region of UE0, and "\" for difference set.

The main advantage of the proposed partial ICIC is as follows: i) it can detect and mitigate ICI effectively by designing of coordination regions, which takes account of the distance between the user and its home BS, downlink transmission power, and density of interferers; ii) it reduces the computational complexity and improves spectral efficiency by designing of the co-channel threshold.




(a) 1-reuse in partial ICIC




(b) 2-BSs coordination in partial ICIC

FIGURE 1. Partial ICIC in the system with PPP distributed BSs; the dots "○" represent UEs

To improve user's performance, the co-channel threshold and the coordination region should be designed to ensure coverage probability is sufficiently large, such that [10]

$$P(SINR > T) \geq \beta \tag{1}$$

where $T$ and $\beta$ ($0 \leq \beta \leq 1$) are SINR threshold and coverage threshold respectively which depend on system requirements.

3. **Derivation of the Co-channel Threshold and the Coordination Region.** In this section, we provide a theoretical framework for deriving the co-channel threshold $\gamma$ and the coordination region. The SINR of a typical user at a distance $r$ from its corresponding home BS denoted as BS1 in Figure 1 can be expressed as

$$SINR = \frac{phr^{-\alpha}}{\sigma^2 + I_\Phi} \tag{2}$$

where $p$ is the transmit power of BS, $h$ represents the small-scale fading obeying the pdf of $h \sim \exp(\mu)$, $\sigma^2$ is the noise power, and $\alpha$ is the path loss exponent, which is generally larger than 2. Hence, $phr^{-\alpha}$ can be regarded as the received signal power. $I_\Phi = \sum\limits_{i\in\Phi} \delta(i) p h_i r_i^{-\alpha}$

is the interference from the set $\Phi$, where $\delta(i)$ is an indicator function that takes the value 1, if BS $i$ is transmitting to its user on the same frequency band as the typical user. It is determined by schedule policy and is hard to model.

**Lemma 3.1.** *When BSs are modeled as a PPP of density $\lambda$ and the nearest interferer to the typical user is at least at a distance $d$, the coverage probability of the typical user in the downlink can be described as*

$$P_C \triangleq e^{-\mu T \sigma^2 r^\alpha / p} e^{-\pi\lambda\rho(T,\Delta,d,r)} \tag{3}$$

*where* $\rho(T,\Delta,d,r) = T^{2/\alpha} r^2 \Delta \cdot \int_{\left(\frac{d}{rT^{1/\alpha}}\right)^2}^{\infty} \left(\frac{1}{1+u^{\alpha/2}}\right) du$; $\Delta = E\delta(i)$; $\delta(i)$ *is an indicator function that takes the value* 1*, if BS $i$ is transmitting to its user on the same frequency band as the typical user; Hence,* $\Delta = 1$ *if all BSs share the same frequency band, and* $\Delta = 1/3$ *if* $1/3$ *of the BSs share the same frequency band. $T$ is the SINR threshold which is determined by system requirements. $h$ represents the small-scale fading obeying the pdf of* $h \sim \exp(\mu)$*. $\alpha$ is the path loss exponent. Generally, $d$ is larger than $r$ because of the smallest distance cell association in practice systems.*

**Proof:** We denote $\hat{\Phi}$ as the interference set. For the given values of $r$ and $d$, the coverage probability $P_C$ can be expressed as

$$\begin{aligned} P_C &\triangleq P(SINR > T) = P\left(\frac{phr^{-\alpha}}{\sigma^2 + I_{\hat{\Phi}}} > T\right) \\ &\overset{(a)}{=} E\left(e^{-\mu T\left(\sigma^2 + I_{\hat{\Phi}}\right) r^\alpha p^{-1}}\right) \\ &= e^{-\mu T \sigma^2 r^\alpha p^{-1}} E\left(\prod_{i\in\hat{\Phi}}\left(1 - \delta(i)\left(1 - e^{-\mu T r^\alpha h_i r_i^{-\alpha}}\right)\right)\right) \\ &\overset{(b)}{=} e^{-\mu T \sigma^2 r^\alpha p^{-1}} e^{-2\pi\lambda\int_d^\infty \Delta\left(1 - \frac{\mu}{\mu + \mu T r^\alpha x^{-\alpha}}\right) x dx} \\ &\overset{(c)}{=} e^{-\mu T \sigma^2 r^\alpha p^{-1}} e^{-\pi\lambda T^{2/\alpha} r^2 \Delta \int_{\left(\frac{d}{rT^{1/\alpha}}\right)^2}^{\infty}\left(\frac{1}{1+u^{\alpha/2}}\right) du} \\ &\overset{(d)}{=} e^{-\mu T \sigma^2 r^\alpha / p} e^{-\pi\lambda\rho(T,\Delta,d,r)} \end{aligned} \tag{4}$$

where (a) follows from the exponential distribution of $h$. (b) follows from the probability generating functional [2] of the PPP. The integration limits are from $d$ to $\infty$ since the closest interferer $\left(\in \hat{\Phi}\right)$ is at least at a distance $d$. (c) follows from a change of variables $u = \left(T^{-1/\alpha} x / r\right)^2$. (d) follows from a change of variables

$$\rho(T,\Delta,d,r) = T^{2/\alpha} r^2 \Delta \cdot \int_{\left(\frac{d}{rT^{1/\alpha}}\right)^2}^{\infty} \left(\frac{1}{1+u^{\alpha/2}}\right) du \tag{5}$$

According to Lemma 3.1, in order to satisfy (1), the distance from an interferer to the typical user should be larger than a threshold denoted as $d_{threshold}$ because the coverage probability $P_C$ is an increasing function of $d$. Therefore, we design the coordination region and $d_{threshold}$ as follows.

**Theorem 3.1.** *The coordination region of a typical user is an interior region of a circle with the user as the centre and $d_{threshold}$ as the radius, where*

$$d_{threshold} = \max\left(y^{-1}\left\{-\left(\ln\beta + \mu T\sigma^2 r^\alpha / p\right) / (\pi\lambda)\right\}, r\right) \tag{6}$$

*where* $y(d) \triangleq T^{2/\alpha} r^2 \Delta \cdot \int_{\left(\frac{d}{rT^{1/\alpha}}\right)^2}^{\infty} \left(\frac{1}{1+u^{\alpha/2}}\right) du$; $y^{-1}$ *is the inverse function determined by $y$ uniquely.*

**Proof:** To obtain the expression of $d_{threshold}$, we solve the following inequality:

$$P_C \triangleq e^{-\mu T\sigma^2 r^\alpha/p} e^{-\pi\lambda\rho(T,\Delta,d,r)} \geq \beta \tag{7}$$

which, using the change of variable $y(d) \triangleq \rho(T, \Delta, d, r)$, can be rewritten as

$$y(d) \leq -\left(\ln\beta + \mu T\sigma^2 r^\alpha/p\right)/(\pi\lambda) \tag{8}$$

By calculating the inverse function of (8), we have

$$d \geq y^{-1}\left\{-\left(\ln\beta + \mu T\sigma^2 r^\alpha/p\right)/(\pi\lambda)\right\} \tag{9}$$

Because of the smallest distance cell association and (9), the proof of Theorem 3.1 is finished.

Especially, if $\alpha = 4$, $d_{threshold}$ can be expressed as

$$\max\left(rT^{1/\alpha}\sqrt{tg\left(\pi/2 + \frac{\ln\beta + \mu T\sigma^2 r^\alpha p^{-1}}{\pi\lambda T^{2/\alpha} r^2}\Delta\right)}, r\right) \tag{10}$$

Based on Theorem 3.1, we focus on the co-channel threshold in Corollary 3.1, where single-BS serving is employed for the users who have a distance lower than the co-channel threshold from its home BS.

**Corollary 3.1.** *1-reuse scheme could be employed to users when they have a distance less than $f^{-1}(-\ln\beta)$ to their home BS. Here, $f^{-1}$ is the inverse function of $f(r)$, $f(r) = \pi\lambda T^{2/\alpha} r^2 \int_{T^{-2/\alpha}}^{\infty}\left(\frac{1}{1+u^{\alpha/2}}\right)du + \mu T\sigma^2 r^\alpha/p$, and $\gamma = f^{-1}(-\ln\beta)$ is the co-channel threshold.*

**Proof:** In (6), we consider the case when

$$r \geq y^{-1}\left\{-\left(\ln\beta + \mu T\sigma^2 r^\alpha/p\right)/(\pi\lambda)\right\} \tag{11}$$

Then, according to the smallest distance cell association and (11), we have

$$d_{nearest} \geq r \geq y^{-1}\left\{-\left(\ln\beta + \mu T\sigma^2 r^\alpha/p\right)/(\pi\lambda)\right\} \tag{12}$$

where $d_{nearest}$ is the distance between the nearest interference BS and the typical user.

Furthermore, according to (9), we obtain that the coverage probability of the typical user will be larger than $\beta$ when $d_{nearest} \geq y^{-1}\{-(\ln\beta + \mu T\sigma^2 r^\alpha/p)/(\pi\lambda)\}$. Therefore, when (11) is satisfied, the coverage probability of the typical user will be larger than $\beta$.

Resolving (11), we have

$$T^{2/\alpha} r^2 \Delta \cdot \int_{T^{-2/\alpha}}^{\infty}\left(\frac{1}{1+u^{\alpha/2}}\right)du \leq -\left(\ln\beta + \mu T\sigma^2 r^\alpha/p\right)/(\pi\lambda) \tag{13}$$

To get the co-channel threshold, we substitute $\Delta = E\delta(i) = 1$ into (13) and have

$$\pi\lambda T^{2/\alpha} r^2 \int_{T^{-2/\alpha}}^{\infty}\left(\frac{1}{1+u^{\alpha/2}}\right)du + \mu T\sigma^2 r^\alpha/p \leq -\ln\beta \tag{14}$$

where $\Delta = E\delta(i) = 1$ means that the co-channel operation is employed to users in the shadow areas shown in Figure 1.

Denoting the left part of (14) as $f(r)$, we have

$$f(r) \leq -\ln\beta \tag{15}$$

Calculating the inverse function for an increasing function $f(r)$ in (15), we prove the corollary.

4. **Performance Analysis.** In this section, we evaluate the performance of the proposed partial ICIC scheme in random wireless networks. Here, radius of cells is 1km; users are uniformly distributed in the network; $\lambda = 1/\text{km}^2$; transmit power of BSs is 46dBm; $\alpha = 4$; $T = -4$dB; the number of sub-carriers is 600; the capacity of user $i$ is calculated as $C_i = \Delta B \log(1 + SINR_i)$, where $\Delta B$ is the bandwidth.

Figure 2 displays relationships between the radius of the coordination region and $\beta$ for different values of $r$ and $\Delta$. As observed, the radius of the coordination region increases with the increase of $r$ and $\beta$, while decreases with the increase of the schedule policy $\Delta$. It also indicates that users far away from their home BS need more coordinating BSs.

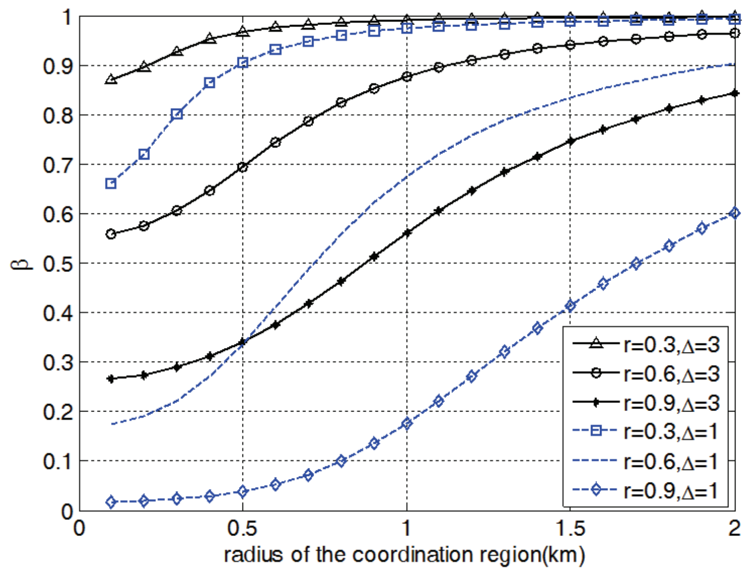



FIGURE 2. Radius of the coordination region vs. $\beta$

In what follows, system level simulation results are given in Figure 3 and Figure 4. In Figure 3, we give cell-edge user average capacity as a function of the average number of users per cell. Performance of partial ICIC is compared with 1-reuse scheme. As observed, partial ICIC achieves high capacity performance to 1-reuse scheme especially for large burden systems.

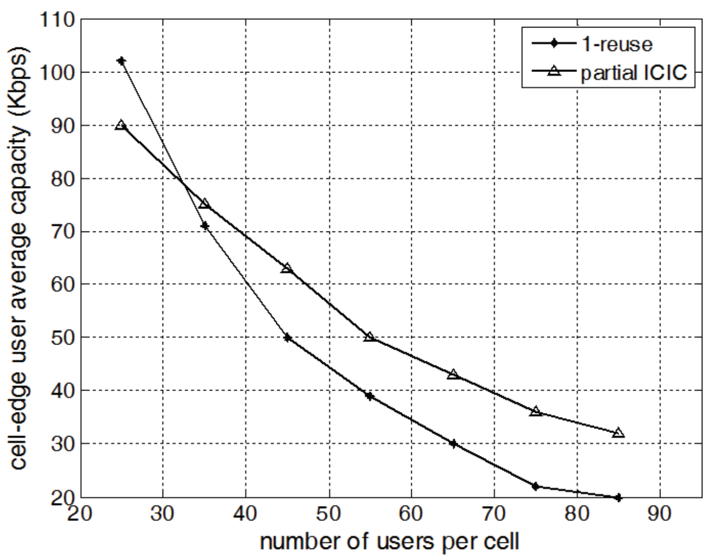



FIGURE 3. Comparison of cell-edge user average capacity with $\gamma = 0.6$km

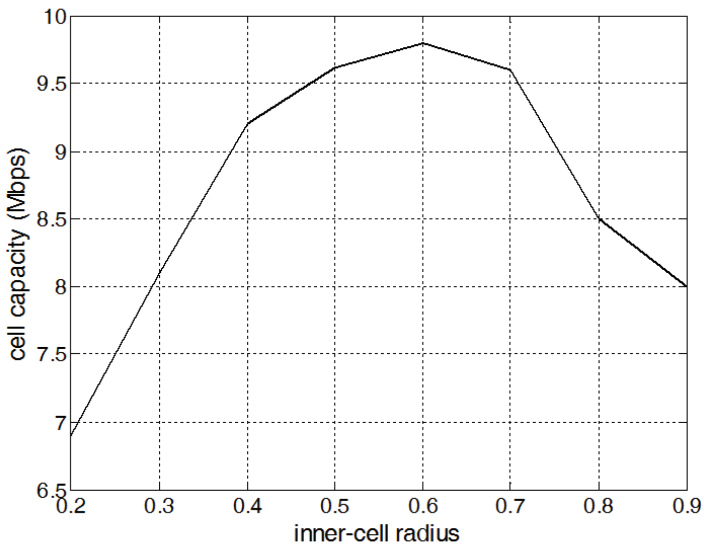



Figure 4. Cell capacity as a function of inner-cell radius

We do simulations with different values of inner-cell radius varying from 0.2 to 0.9 in Figure 4. The average number of users in each cell is 65. Figure 4 shows that the average cell capacity of partial ICIC first increases and then decreases. As inner-cell radius increases, the increase in cell capacity decreases, since the number of allocated sub-carriers for inner-cell users is insufficient and results in greater interference for these users.

5. **Conclusions.** To mitigate inter-cell interference and satisfy coverage requirements for users, we propose a partial ICIC scheme for cellular networks using PPP. Different from publishing papers, in partial ICIC, each user selects the coordinating base stations based on its coordination region, which is derived based on the stochastic geometry theory. The co-channel threshold is further derived based on the expression of coordination region. The users, who have a distance lower than the co-channel threshold from their home BS, employ 1-reuse. Correspondingly, the frequency reuse factor of the rest of users is determined by the coordination region of the user. Furthermore, other resource coordination schemes, such as power and time, could be investigated to satisfy the requirement users' quality of service (QoS).

**Acknowledgment.** This work is supported in part by Natural Science Foundations of Zhejiang Province (LQ15F010004), and the National Natural Science Foundation of China (61401130, 61501158).

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