Performance Evaluation of Joint Power and Frequency-Domain Interference Coordination in Heterogeneous Networks

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Abstract
We evaluate our previously reported joint power and frequency-domain inter-cell interference coordination (ICIC) method for heterogeneous networks where low transmission-power pico base stations (BSs) overlay onto a high transmission-power macro BS. In the previously reported method, to protect users connected to a pico BS from interference from a high-power macro BS, we define a protected band, which is exclusively used by only pico BSs. In the remaining non-protected band, we employ soft fractional frequency reuse (SFR) at the macro BSs so that macro-to-macro ICIC is achieved. With this frequency usage, we employ adaptive transmission power control for the non-protected band at the macro BS and simultaneously control the bandwidth allocation to the protected band from the viewpoint of proportional fairness (PF). The previously reported method is achieved with very limited information exchange between BSs. The transmission power control is a decentralized approach. Thus, in this method, we use a cost function in the objective function to lower the transmission power of the macro BSs so that the interference to the other BSs is considered. In our previous investigation, we used different values of the cost for different system conditions. In this paper, we use the same value of the cost for all evaluated conditions to obtain more realistic results. Computer simulation results show in detail the effectiveness of our method compared with conventional approaches under various system conditions.

1. Introduction
Heterogeneous networks, in which low transmission-power pico base stations (BSs) overlay onto a high transmission-power macro BS, have recently attracted much attention [1-3]. Heterogeneous networks are considered to be a cost efficient solution to address the exponentially increasing volume of data traffic in current cellular networks in the 3rd Generation Partnership Project (3GPP) Long Term Evolution-Advanced (LTE-Advanced) system [4, 5]. To enhance the overall system performance in a heterogeneous network, inter-cell interference coordination (ICIC) [6] is essential. The main source of inter-cell interference is the macro BS, whose transmission power is high. To avoid imparting severe interference from the macro BSs to users connected to different BSs, various methods have been studied. In [7], we reported a joint macro-to-macro and macro-to-pico ICIC method for heterogeneous networks. In the method, a protected band is defined within the overall system bandwidth, which is exclusively used by only pico BSs, in order to alleviate the macro-to-pico interference [1-3, 8, 9]. In the remaining frequency band, which is called the non-protected band in this paper, we employ fractional frequency reuse (FFR) at the macro BSs so that the macro-to-macro ICIC is achieved [10-14]. Furthermore, in [15], the bandwidth allocation to the protected band and the transmission power of the macro BSs are jointly and adaptively controlled from the viewpoint of proportional fairness (PF) [16, 17]. More specifically, we employed adaptive power control for the macro BSs assuming frequency usage based on soft FFR (SFR) [10]. The proposed method jointly optimizes the cell association (the decision regarding which BS serves which users), the bandwidth allocation to the protected band, control of the total transmission power at the macro BS, and the power splitting among different frequency blocks in SFR at the macro BS. By performing an iterative process with the aid of very limited information exchange between BSs regarding the number of users connected to each BS, this joint optimization is achieved without relying on complicated inter-BS cooperation. Computer simulation results show the effectiveness of the previously reported method under various system conditions. However, in our previous investigation in [15], we used different values of the cost for different system conditions, which may be difficult to assume in a real system. In this paper, we use the same value of the cost for all evaluated conditions to obtain more realistic results. Computer simulation results show in detail the effectiveness of our method compared with conventional approaches under various system conditions.

The remainder of the paper is organized as follows. First, Sect. 2 describes our previously reported method. Section 3 presents a performance evaluation based on system-level simulation results on the system-level throughput. Finally, Sect. 4 concludes the paper.

2. Proposed Method
In this section, we describe our previously reported method in [15] (hereafter denoted as the proposed method). We assume that there are set $N_{macro}$ of macro BSs and set $N_{pico}$ of pico BSs in the system, where all BSs share the same overall system transmission band. The overall system transmission bandwidth is denoted as $W_c$. Figure 1 shows the frequency resource usage in the proposed method. A fraction of the overall system transmission bandwidth, $W_{np} = (1-\alpha)W_c (0 \leq \alpha < 1)$, is used for
all BSs and is called the non-protected band. The remaining bandwidth, $W_p = \alpha W_m$, is the protected band and is used by only the pico BSs. The use of the protected band effectively alleviates the impact of macro-to-pico interference and enhances the traffic-load balancing effect via the use of pico BSs.

In the non-protected band, FFR is applied to alleviate the impact of macro-to-macro interference. We use SFR [10] as a typical FFR method in this paper. In SFR, one-third of the non-protected band, which does not overlap among the three neighboring macrocells, is called an edge band. The remaining two-thirds of the non-protected band is called an inner band. The transmission power density for the edge band at macro BS $n \in N_{macro}$ is set to be higher than that for the inner band. These settings yield the ICIC effect for the edge band since the increased transmission power density for the edge band and the reduced transmission power density for the inner band of neighboring cells result in a better signal-to-inter-macrocell interference power ratio at the edge band. For simplicity in the explanation hereafter, we define four frequency blocks, where frequency blocks $f = 1, 2, 3$ correspond to the three respective frequency bands within the non-protected band, while frequency block 4 corresponds to the protected band, as shown in Fig. 1. For a given $\alpha$, the bandwidth of the respective frequency blocks, $W_f$, is represented as

$$W_f = \begin{cases} W_p - (1-\alpha)W_i, & f = 1, 2, 3 \\ W_p = \alpha W_i, & f = 4 \end{cases}$$ (1)

The frequency block index corresponding to the edge band of macro BS $n \in N_{macro}$ is denoted as $f_{edge}(n) \in \{1, 2, 3\}$. Between the neighboring macro BS $n$ and BS $m$, $f_{edge}(n) \neq f_{edge}(m)$.

The optimal sets of $\alpha$, $\{p_n\}$, and $\{\beta_n\}$ should be dependent on the user distribution within the system coverage. The proposed method optimizes them from the viewpoint of PF. PF-based resource allocation is known to achieve a good tradeoff between system efficiency and user fairness by maximizing the log-sum user throughput (in other words, the geometric mean user throughput) [16, 17].

The proposed method is implemented by an iterative process having multiple steps as shown in Fig. 2. In the following, we describe the process of each step.

**Step 1: Cell Association**

In Step 1, the cell association, i.e., the control of the BSs that serve the respective users, is updated for a given set of $\{p_n\}$. In this step, we use the cell range expansion (CRE) method in [8]. In the CRE, the coverage of the pico BSs is extended for better traffic-load balancing. The CRE introduces bias to the reference signal received power (RSRP) during the decision of user association depending on the transmission power of each BS, $p_n$. The user is associated with the BS that has the highest biased RSRP. In the following evaluation, the bias to the RSRP of each pico BS is set to 16 dB. We assume

$$q_{n, f}(\alpha, \beta_n, p_n) = \begin{cases} q_n(\alpha, p_n, \beta_n), & n \in N_{macro}, f = f_{edge}(n) \\ 3(1-\beta_n)p_n/(1-\alpha)W_i, & n \in N_{macro}, f = 1, 2, 3 \neq f_{edge}(n) \\ 3(1-\beta_n)p_n/(1-\alpha)W_i, & n \in N_{macro}, f = 4 \\ 0, & n \in N_{pico}, f = 1, 2, 3, 4 \end{cases}$$ (2)

The transmission power of BS $n$ is denoted as $p_n$. For pico BS $n \in N_{pico}$, $p_n$ is fixed to $P_{pico}$. For macro BS $n \in N_{macro}$, $p_n$ is adaptively controlled within the range of zero to $P_{macro}$. At macro BS $n$, the power allocation ratio to the edge band, $f_{edge}(n)$, is denoted as $\beta_n (0 \leq \beta_n \leq 1)$, which will be adaptively controlled in the proposed method. The transmission power density of BS $n \in N_{macro} \cup N_{pico}$ at frequency block $f$ is denoted as $q_{n, f}(\alpha, p_n, \beta_n)$ for given $\alpha$, $p_n$, and $\beta_n$. The term $q_{n, f}(\alpha, p_n, \beta_n)$ is represented as

**Step 2: Protected bandwidth control**

**Step 3: Transmission power control of macro BS**

**End**

Figure 2: Proposed iterative algorithm

A. **Step 1: Cell Association**

In Step 1, the cell association, i.e., the control of the BSs that serve the respective users, is updated for a given set of $\{p_n\}$. In this step, we use the cell range expansion (CRE) method in [8]. In the CRE, the coverage of the pico BSs is extended for better traffic-load balancing. The CRE introduces bias to the reference signal received power (RSRP) during the decision of user association depending on the transmission power of each BS, $p_n$. The user is associated with the BS that has the highest biased RSRP. In the following evaluation, the bias to the RSRP of each pico BS is set to 16 dB. We assume
that the set of users $K_n$ to be served by BS $n$ is decided in Step 1.

### B. Step 2: Protected Bandwidth Control

In Step 2, the $\alpha$ value is optimized to maximize the log-sum user throughput for a given user association, $\{p_n\}$, and $\{\beta_n\}$. The average path gain between user $k \in K_n$ served by BS $n$ and BS $m$ is denoted as $g_{k,m}$. The link-level throughput of user $k$ of BS $n$ obtained at frequency block $f$, $r_{n,k,f}$ (b/s/Hz), is represented as

$$ r_{n,k,f} = \log_2 \left( 1 + \frac{g_{n,k} q_{n,f}}{\sum_{m=N_{macro}}^{N_{user}} g_{n,m} q_{m,f} + N_0} \right) $$

(3)

where $N_0$ is the receiver noise power density.

Assuming that the bandwidth allocated to user $k$ of BS $n$ at frequency block $f$ is $\rho_{n,k,f}$, the throughput of user $k$ of BS $n$ is represented as

$$ R_{n,k} = \sum_{f=1}^{4} \rho_{n,k,f} r_{n,k,f} $$

(4)

From [18], the optimal set of $\{\rho_{n,k,f}\}$ at BS $n$ from the viewpoint of PF (i.e., to maximize the log-sum of $R_{n,k}$) is calculated as

$$ \rho_{n,k,f} = \max \left\{ 0, \frac{1}{\mu_{n,f}} \sum_{f'=1}^{4} \rho_{n,k,f'} r_{n,k,f'} \right\} $$

(5)

where $\mu_{n,f}$ is set so that $\sum_{k \in K_n} \rho_{n,k,f} = W_f$.

In PF, among the $|K_n|$ users served by BS $n$, the number of users who are simultaneously allocated resources from each combination of two frequency blocks is at most one. Furthermore, equal amounts of resources are allocated among users to which the same frequency block is allocated. On the basis of this fact, the quasi-optimal $\alpha$ value for a given set $\{\rho_{n,k,f}\}$ is obtained as $[7]

$$ \alpha = \sum_{m=N_{macro}}^{N_{user}} \left| K_{n,m} \right| / \sum_{m=N_{macro}}^{N_{user}} \sum_{f=1}^{4} \left| K_{n,f} \right| $$

(6)

where $K_{n,m}$ is the set of users allocated the frequency block $f$ at BS $n$, which is obtained from $\{\rho_{n,k,f}\}$. Thus, by exchanging a very small amount of information regarding the number of users connected to different frequency blocks among BSs, the optimal $\alpha$ value for a given user distribution is controlled in the proposed method.

Since the optimal $\{\rho_{n,k,f}\}$ and $\alpha$ are coupled, the proposed method repeats the calculation of Eqs. (5) and (6) until convergence in Step 2.

### C. Step 3: Transmission Power Control at Macro BSs

In Step 3, the sets $\{p_n\}$ and $\{\beta_n\}$ are optimized for a given user association and $\alpha$. The power control problem in the multicell scenario is known to be nonconvex in general, and complicated inter-BS cooperation is necessary to obtain the globally optimal solution. The proposed method employs a decentralized approach so that complicated inter-BS cooperation and a large amount of information exchange among BSs regarding the channel state information are avoided.

The optimization problem in Step 3 at macro BS $n$ is represented as

$$ \begin{align*}
    & \arg \max_{p_n, \beta_n} U_n = \sum_{k \in K_n} \log R_{n,k} - \delta_1 \beta_n p_n - \delta_2 \frac{(1-\beta_n) p_n}{2} \\
    \text{s.t.} & \quad 0 \leq p_n \leq P_{\text{macro}}, \quad 1/3 \leq \beta_n \leq 1, \quad \rho_{n,k,f} \geq 0 \forall k, f, \quad \sum_{k \in K_n} \rho_{n,k,f} = W_f \forall f
\end{align*} $$

(PI)

Note that during the optimization of (P1), $\{p_n\}$ and $\{\beta_n\}$ of neighboring BSs are assumed to be the same levels as in the previous time duration. Thus, $R_{n,k}$ is calculated based on the previous feedback of the average signal-to-interference-plus-noise ratio (SINR) of all users belonging to that BS [19]. Since the optimal $p_n$ and $\beta_n$ are dependent on $\{\rho_{n,k,f}\}$, $\{\rho_{n,k,f}\}$ in addition to $p_n$ and $\beta_n$ are simultaneously optimized for given $\{p_n\}$ and $\{\beta_n\}$ of neighboring BSs in Step 3.

The objective function of (P1), $U_n$, contains two cost functions. The first and second cost functions are proportional to the power allocations to the edge band ($\beta_n p_n$) and each inner band ($1-\beta_n) p_n/2$), respectively. Terms $\delta_1$ and $\delta_2$ are positive constants and common to all BSs, and they control the magnitude of the cost for increasing the power allocation to the edge band and inner band, respectively. The reason why the cost functions are proportional to the power allocation to the corresponding bands is to reduce the inter-cell interference by appropriately setting the transmission power for these two bands.

The optimization problem (P1) is a convex problem and the constraints on the variables $p_n$, $\beta_n$, and $\rho_{n,k,f}$ to be optimized are independent. Therefore, the problem can be solved by repeating alternately solving three sub-problems: the optimization of $\{\rho_{n,k,f}\}$ (Step 3a), the optimization of $\beta_n$ (Step 3b), and the optimization of $p_n$ (Step 3c). The optimal $\{\rho_{n,k,f}\}$ is obtained using (5) for a given set of $p_n$ and $\beta_n$. In Step 3b, $\beta_n$ is optimized to maximize $U_n$ for the given $\{\rho_{n,k,f}\}$ and $p_n$ obtained from the previous steps. Since $U_n$ is a convex function of $\beta_n$, the optimal $\beta_n$ is either 1/3, 1, or the $\beta_n$ value at $\partial U_n/\partial \beta_n = 0$. The $\beta_n$ at $\partial U_n/\partial \beta_n = 0$ is searched for by using the bisection method in this paper. Similarly, in Step 3c, the optimal $p_n$ is either 0, $P_{\text{macro}}$, or the $p_n$ value at $\partial U_n/\partial p_n = 0$ for the given $\{\rho_{n,k,f}\}$ and $\beta_n$. The $p_n$ at $\partial U_n/\partial p_n = 0$ is searched for by using the bisection method in this paper.

The above procedure is independently performed at each macro BS $n$, assuming that $p_n$ and $\beta_n$ of neighboring macro BSs $m \neq n$ do not change from those at the previous time. At the next time, since all the macro BSs update their $\{p_n\}$ and $\{\beta_n\}$.
{βn}, the same process is repeated until convergence. Since the proposed method can be categorized as a supermodular game [20], the convergence of \{pn\} and \{βn\} to the Nash equilibrium is guaranteed.

3. Performance Evaluation

We evaluate the user throughput performance of the proposed method by computer simulation. Table 1 gives the simulation parameters. The simulation conditions are based on [5]. A 19-hexagonal macrocell layout is assumed. The pico BSs are located randomly within a macrocell with a 500-m cell radius. The number of pico BSs per macrocell, \(N_{\text{pico}}\), is varied from one to eight. The maximum transmission power levels of the macro and pico BSs, \(P_{\text{macro}}\) and \(P_{\text{pico}}\), are 43 and 27 dBm, respectively. The overall transmission bandwidth, \(W_t\), is 4.32 MHz. Orthogonal frequency division multiple access (OFDMA) is assumed. As the propagation model, distance-dependent path loss and lognormally distributed random shadowing with the parameters given in Table 1 are simulated. The number of users per macrocell is 30. The user locations are uniformly distributed within the macrocell. The user throughput is calculated using the Shannon formula. The cell association is performed using the CRE method [8] with a bias of 16 dB for all pico BSs. We evaluate the geometric mean user throughput of all users within a macrocell coverage area, \(R_{\text{gmean}}\).

| Parameter                          | Value                                                                 |
|------------------------------------|----------------------------------------------------------------------|
| Cell layout                        | 19 hexagonal macrocell model                                        |
| Macrocell radius                   | 500 m                                                                |
| System bandwidth                   | 4.32 MHz                                                             |
| Number of pico BSs per macrocell, \(N_{\text{pico}}\)                | Parameterized from 1 to 8                                           |
| BS transmission power              | Macro BS: 43 dBm, Pico BS: 27 dBm                                   |
| Antenna gain                       | Macro BS: 14 dBi, Pico BS: 5 dBi                                    |
| CRE bias                           | 16 dB                                                                |
| Distance-dependent path loss       | Macro BS: 128.1 + 37.6 log_{10}(r), r: kilometers                   |
| Shadowing correlation among BSs    | 0.5                                                                  |
| Standard deviation of shadowing    | Macro BS: 8 dB, Pico BS: 10 dB                                      |
| Receiver noise power density       | −169 dBm/Hz                                                          |
| Number of user terminals per macrocell | 30                                                                 |

First, we evaluate the average of the convergence values of \(p_n\), \(β_n\), and \(α\) which are variables to be controlled. Figure 3 shows the average values of \(p_n\) and \(β_n\) as a function of \(N_{\text{pico}}\). The cost values \(δ_1\) and \(δ_2\) are respectively set to 0.007 and 0.135 for all macro BSs. When \(N_{\text{pico}}\) is small, the number of users connected to macro BSs is increased. In addition, the probability that users located at the cell edge are connected to macro BSs increases. Since the throughput levels of these users are under a power-limited condition, \(p_n\) and \(β_n\) are controlled to large values in order to improve the throughput levels of these users. As \(N_{\text{pico}}\) increases, the number of users connected to macro BSs decreases. Therefore, more users are under a bandwidth-limited condition regarding the achievable throughput, and the values of \(p_n\) and \(β_n\) are controlled by the proposed method to be small. Thus, the proposed method adaptively controls the transmission power settings of macro BSs to reduce the inter-cell interference.

Figure 4 shows the \(α\) value controlled by the proposed method as a function of \(N_{\text{pico}}\). When \(N_{\text{pico}}\) is small, the number of users connected to pico BSs tends to be small. Therefore, \(α\) is controlled to a small value. Since the number of users connected to the pico BSs increases as \(N_{\text{pico}}\) increases, the value of \(α\) is controlled to a larger value in order to avoid interference from macro BSs to these users. However, since the transmission power of the macro BS is also controlled at the same time, the value of \(α\) starts to decrease when \(N_{\text{pico}}\) is larger than 4 under the evaluated simulation condition. From this observation, it is considered that the proposed method can appropriately control \(α\) in conjunction with the control of \(p_n\) and \(β_n\).

Fig. 5 shows the geometric mean user throughput, \(R_{\text{gmean}}\), as a function of \(N_{\text{pico}}\). For comparison, the cases when no adaptive control is assumed are also shown. In cases without adaptive control, the \(α\) value is set to be the best average value for corresponding \(N_{\text{pico}}\) values. The combination of \(β_n = 13\) dB and \(p_n = 27\) dBm is the best setting on average for \(N_{\text{pico}}\) of zero. The
combination of $\beta_m = 26$ dB and $p_n = 5$ dBm is the best setting on average for $N_{\text{pico}}$ of eight. When we do not apply the adaptive control of $p_n$ and $\beta_m$, $R_{\text{gmean}}$ is degraded when the $N_{\text{pico}}$ value is different from the value with which $p_n$ and $\beta_m$ are optimized. The proposed method achieves the highest $R_{\text{gmean}}$ regardless of the $N_{\text{pico}}$ value since the proposed method jointly optimizes $\{p_n\}$ and $\{\beta_m\}$ for a given user and macro/pico BS distributions within the system coverage.

4. Conclusion

We evaluated our previously reported joint power and frequency-domain ICIC method for heterogeneous networks where low transmission-power pico BSs overlay on a high transmission-power macro BS. In the previously reported method, to protect users connected to a pico BS from interference from high-power macro BS, we define the protected band, which is exclusively used by only pico BSs. In the remaining non-protected band, we employ SFR at the macro BSs so that macro-to-macro ICIC is achieved. With this frequency usage, we employ adaptive transmission power control for the non-protected band at the macro BS and simultaneously control the bandwidth allocation to the protected band from the viewpoint of PF. The previously reported method is achieved with very limited information exchange between BSs. The transmission power control is a decentralized approach. Thus, in this method, we use the cost function in the objective function to lower the transmission power of the macro BSs so that the interference to the other BSs is considered. We showed that even if we use the same value of the cost for all the evaluated system conditions, the previously reported method effectively works. Computer simulation results showed in detail the effectiveness of the previously reported method under various system conditions.

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