Potential Game Approach for Self-Organization Scheme in Open Access Heterogeneous Networks

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***Abstract*—In the present paper, a self-organization scheme for joint base station selection and resource block allocation in an OFDMA cellular network is proposed. The network consists of overlaying macrocell and indoor picocells with open access configuration. Inspired by the cognitive radio technology, each mobile user in heterogeneous network selects the most appropriate base station and allocates resource blocks in a decentralized fashion in order to manage the cross- and co-tier interference, and improve the throughput performance. The problem is formulated as a potential game, which is demonstrated to converge to a Nash equilibrium when distributed sequential play based on the best response dynamics is adopted. The simulation results show that the proposed self-organization scheme improves the uplink system capacity of the heterogeneous networks with a slight loss of the picocell performance.**

I. Introduction

With the aim to provide the benefit to both end-users and network operators, low-cost and short-range indoor base stations such as femtocells and picocells have been proposed as an emerging solution for enhancing the indoor coverage and capacity of future cellular systems [1]. A femto base station, which is known as Home eNB (HeNB) in 3GPP LTE terminology, is usually installed and controlled in residential and office environments by end-users. On the other hand, an indoor pico base station or pico eNB is generally deployed by network operators in large buildings or public spaces such as shopping malls, railway stations, and airports.

By embedding the low-power base stations inside a macrocell coverage, a heterogeneous network is constructed, and thus, the enhancement of network capacity in indoor environments can be obtained. In spite of advantages in deploying the indoor base stations, several technical challenges have to be overcome, mainly cross- and co-tier interference issues in co-channel operation of picocells or femtocells [2], [3]. Cross-tier interference refers to the interference between picocell or femtocell tier and macrocell tier. Moreover, the interference may occur between neighboring picocells or femtocells, which is known as co-tier interference. Thus, mitigating the cross- and co-tier interference is an indispensable task in heterogeneous network development.

Another aspect that has to be considered in deploying indoor base stations with co-channel operation is access control mechanism. In general, two access control mechanisms are identified: closed access and open access. The closed access configuration is mainly used in femtocell to allow only a subscriber group to use the femtocell service. Thus, privacy and security in using the femtocell service can be ensured. In [4]–[6], the feasibility of co-channel operation and interference mitigation strategies with closed access configuration in heterogeneous networks have been investigated. The previous works have shown that the destructive cross-tier interference problem is potentially introduced in the closed access configuration, i.e., macro users that lie on the macrocell edge but close to the HeNB. On the other hand, open access configuration offers an inexpensive solution for expanding the network capacity and mitigating the cross-tier interference problem by allowing any arbitrary non-subscriber group to make a handoff to a close-by indoor base station. In [7], the authors proposed an intermediate access scheme for orthogonal frequency-division multiple access (OFDMA) femtocells, where non-subscriber users are allowed to connect to a femtocell with a limited access to the femtocell resources. In the study reported in [8], the tradeoff between the closed and open access on the system performance was evaluated for HSDPA femtocells. However, most of the previous studies focused on the downlink performance in a centralized way and less attention has been given to analyze the uplink performance of the heterogeneous networks.

In this paper, a self-organization scheme for uplink transmission in heterogeneous networks is proposed. The network consists of overlaying macrocell and indoor picocells with open access configuration. Inspired by the cognitive radio technology [9], each mobile user, which is referred to as user equipment (UE), dynamically learns the surrounding environment and selects the most appropriate strategy combination of base station (eNB) and resource blocks (RBs) in a decentralized manner. We model the self-organization scheme by using a game-theoretic approach, which has been known as a good mathematical tool for modeling the interactions among autonomous entities and extensively used for distributed resource management in wireless networks [10]–[12].

The contributions of this paper are twofold. First, we propose a decentralized scheme for joint base station selection and RB allocation in open access heterogeneous networks. Second, we model the proposed approach as a potential game. Specifically, we propose a utility function that characterizes the player's preference for a particular strategy combination of eNB and RBs. Thus, by adopting the best response dynamics, in which the player chooses the best strategy in response the

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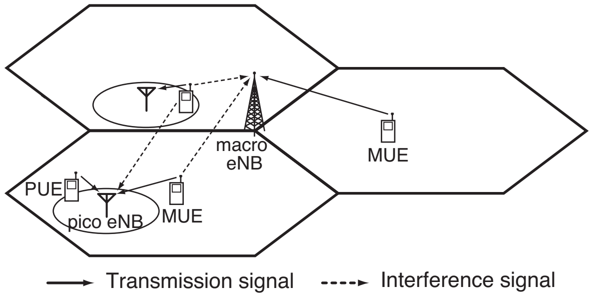

Fig. 1. System model of heterogeneous network in central macrocell site. In open access deployment, macro UEs are allowed make a handoff to the close-by pico eNB.

strategies selected by the other players, the convergence to a Nash equilibrium is ensured. Such equilibrium indicates a steady-state condition at which no player would deviate from its best strategy. Our work is fundamentally different from the work that was proposed in [11]. While the previous work considered only a single channel allocation to mitigate the co-tier interference in cognitive radio networks, in this work, we consider the joint eNB selection and multiple RBs allocation as a composite strategy to mitigate the cross- and co-tier interference, and improve the system performance in the heterogeneous networks.

The remainder of this paper is organized as follows. The system model of a heterogeneous network is described in Section II. Section III presents the potential game framework and the proposed self-organization scheme. The simulation results are presented in Section IV. Finally, Section V summarizes the conclusions of the paper.

II. System Model

We consider the uplink transmission in an OFDMA cellular network. In such a network, the system bandwidth W is divided into K subchannels or resource blocks (RBs). In 3GPP-LTE specification, an RB is defined as the smallest time-frequency resource unit that can be allocated to a user [13]. The network consists of 19 macrocell sites, each of which has three hexagonal sectors. In each sector of macrocells, U_{M} macro UEs (MUEs) are randomly dropped, either indoor or outdoor. P indoor pico eNBs are randomly deployed in each sector of macrocells, each of which serves U_{P} indoor pico UEs (PUEs). Fig. 1 illustrates the model of an open access heterogeneous network with cross- and co-tier interference.

To enhance the spectrum utilization, co-channel operation of macrocell and picocells is considered. In such a scenario, the interference occurs when UE in different cells transmits using the same RB. Each sector of the macrocell is allowed to reuse all spectrum resources. Furthermore, we assume that the OFDMA network is perfectly synchronized.

III. Potential Game Formulation for Joint Base Station Selection and Resource Allocation

A. Potential Game Framework

In order to analyze the behaviors and interactions among autonomous entities in mitigating the cross- and co-tier interference, the self-organization scheme for joint base station selection and resource block allocation is modeled as a potential game. The potential game is a type of strategic non-cooperative game. The non-cooperative game consists of three fundamental components: players, strategies, and utilities. Every player i in the finite set of players $\mathcal{N}$ attempts to choose the best strategy so as to maximize its own utility [14]. The utility function of player i, $u_i : \mathcal{S} \rightarrow \mathbb{R}$, maps the strategy profiles of all players, $\mathcal{S} = \prod_{i\in\mathcal{N}} \mathcal{S}_i$, to a real value $\mathbb{R}$. The strategies of the other players are denoted as $\boldsymbol{s}_{-i} = (s_1, \dots, s_{i-1}, s_{i+1}, \dots, s_N)$.

In our proposed game, the players are MUEs and PUEs, and these are assumed to have cognitive radio capabilities. The set of strategies is the combination of base station (eNB) and resource blocks (RBs), $s_i = (b_i, \boldsymbol{r}_i) \in \mathcal{S}_i$, where $b_i \in B$ is the eNB that is selected by UE i, B is the set of eNBs in the central macrocell site, either the sectors of macro eNB or pico eNBs, $\boldsymbol{r}_i = (k_i^{(0)}, k_i^{(1)} \dots, k_i^{(L-1)}) \in \mathcal{S}_i$ is a subset of RBs utilized by UE i, $k_i^{(l)} \in \boldsymbol{r}_i$ is an element of the set of selected RBs at position l, and L is the number of the selected RBs for transmission. The proposed utility for each UE is a function of cross- and co-tier interference and satisfaction to improve the throughput performance.

A key technique in updating the strategy in the potential game is known as the best response dynamics. In this update strategy, a player chooses a strategy that maximizes its own utility, in response to the current strategies of the other players [15]. The best response strategy of the player i to the strategy profile $\boldsymbol{s}_{-i}$ at time $t+1$, $s_i^{(t+1)}(\boldsymbol{s}_{-i})$, is a strategy that satisfies

$$s_i^{(t+1)} \in \arg\max_{s_i' \in \mathcal{S}_i} u_i(s_i', \boldsymbol{s}_{-i}^{(t)}), \tag{1}$$

where $(s_i^{(t)}, \boldsymbol{s}_{-i}^{(t)}) \in \mathcal{S}$ denotes the strategy profile at time t.

As a commonly-used solution concept in a non-cooperative game, the Nash equilibrium indicates a steady state condition of the strategies of all players [14]. A set of pure strategy profiles of all players, $\boldsymbol{s}^\star = (s_i^\star, \boldsymbol{s}_{-i}^\star) \in \mathcal{S}$ is a Nash equilibrium if and only if satisfies the following condition

$$u_i(s_i^\star, \boldsymbol{s}_{-i}^\star) \geq u_i(s_i', \boldsymbol{s}_{-i}^\star),\ \forall s_i' \neq s_i^\star, \forall s_i' \in \mathcal{S}_i,\ \forall i \in \mathcal{N}. \tag{2}$$

Thus, if a player deviates from its strategy, the utility of the corresponding player would not increase.

A strategic game is called an exact potential game [16] if there exists a potential function $P : \mathcal{S} \rightarrow \mathbb{R}$ that satisfies

$$P(s_i', \boldsymbol{s}_{-i}) - P(s_i, \boldsymbol{s}_{-i}) = u_i(s_i', \boldsymbol{s}_{-i}) - u_i(s_i, \boldsymbol{s}_{-i}), \tag{3}$$

where $s_i' \in \mathcal{S}_i$. In other word, the potential function models the information related to the improvement path of the game, in which the improvement in the utility of a player is exactly equal to the improvement in the potential function.

B. Proposed Scheme

The proposed self-organization scheme consists of three main phases that resemble the cognitive cycle [9]: sensing phase, learning phase, and tuning phase. In this scheme, all UE transmitters sequentially execute the algorithm shown in

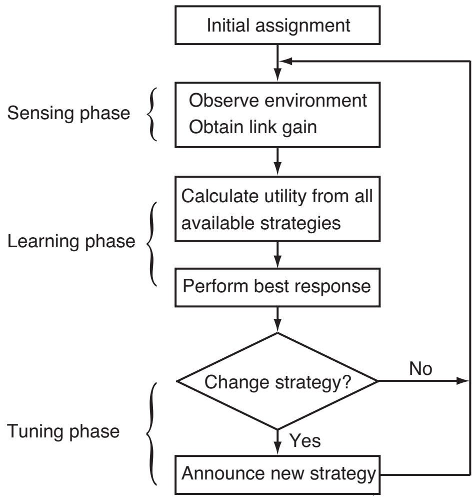

Fig. 2. Flowchart of the proposed self-organization scheme.

Fig. 2. In the sensing phase, we assume that each UE can estimates the link gain to all eNBs and that no collision occur during this phase. For the learning phase, we propose a utility function for each UE in the heterogeneous network that takes into account the cross- and co-tier interference, and the satisfaction of the UE to improve its own throughput by making a handoff to another eNB:

$$u_i(s_i, \boldsymbol{s}_{-i}) = \sum_{x=0}^{L-1}\left[\sum_{y=0}^{L-1}\left(-\sum_{j=1,j\neq i}^{N} G_j^{b_i} p_j^{k_j^{(y)}} \delta_{k_i^{(x)} k_j^{(y)}} - \sum_{j=1,j\neq i}^{N} G_i^{b_j} p_i^{k_i^{(x)}} \delta_{k_j^{(y)} k_i^{(x)}}\right) + \left(G_i^{b_i} p_i^{k_i^{(x)}}\right)\right], \quad (4)$$

where $p_j^{k_j^{(y)}}$ denotes the transmit power of the UE transmitter j in RB $k_j^{(y)}$, $G_j^{b_i}$ denotes the link gain between the UE transmitter j and the eNB b_i that serves the UE i, N is the total number of players, which can be calculated as $N = 3(U_{\mathrm{M}} + PU_{\mathrm{P}})$, and $\delta_{k_i^{(x)} k_j^{(y)}}$ is the interference function that indicates whether or not the element of the selected RBs $\boldsymbol{r}_i$ and $\boldsymbol{r}_j$ are the same: if $k_i^{(x)} = k_j^{(y)}$, $\delta_{k_i^{(x)} k_j^{(y)}} = 1$; otherwise, $\delta_{k_i^{(x)} k_j^{(y)}} = 0$.

The first two terms in the proposed utility function capture the total interference received by the eNB b_i that serves the UE i and the interference that is potentially generated by the UE transmitter i. In other word, the first two terms take into account the cross- and co-tier interference since the MUE and PUE are belong to different network tiers. Note that the term of eNB refers to either the sector of macro eNB or pico eNB. The last term depends only on the strategy chosen by the UE i, which captures the incentive to improve the throughput by making a handoff to the eNB b_i. Thus, maximizing the first two terms in (4) implies that the UE i attempts to select the RBs that not only receive the total minimum interference but also minimize the total interference to the other UEs. Maximizing the last term implies that the UE i tries to make a handoff to the eNB b_i that has the highest link gain to the corresponding UE. Compared with the single channel allocation that was proposed in [11], our proposed utility function consider the joint strategy for selecting eNB and allocating multiple RBs.

Given the proposed utility function u_i, we formulate the potential function as

$$P(s_i, \boldsymbol{s}_{-i}) = \sum_{i=1}^{N}\sum_{x=0}^{L-1}\left[\sum_{y=0}^{L-1}\left(-\frac{1}{2}\sum_{j=1,j\neq i}^{N} G_j^{b_i} p_j^{k_j^{(y)}} \delta_{k_i^{(x)} k_j^{(y)}} - \frac{1}{2}\sum_{j=1,j\neq i}^{N} G_i^{b_j} p_i^{k_i^{(x)}} \delta_{k_j^{(y)} k_i^{(x)}}\right) + \left(G_i^{b_i} p_i^{k_i^{(x)}}\right)\right]. \quad (5)$$

The proof to show that P is a potential function of the exact potential game is given in the Appendix.

The last part of the self-organization scheme is tuning phase. In this phase, the UE decides whether or not to update its strategy, according the result of the best response strategy. If update strategy is necessary, the UE announces its updated strategy to all neighboring UEs.

IV. Simulation Results

TABLE I
Simulation parameters

Parameter	Value
Cellular layout of macrocell	Hexagonal grid, 19 cell sites 3 sectors per site
Cellular layout of picocell	Circular cell, 1 sector per cell
Macrocell/picocell radius	288.68 m (ISD = 500 m), 40 m
Macro path loss	$128.1 + 37.6 \log_{10}(d_{\mathrm{m}}[\mathrm{km}])$ dB
Pico path loss	$140.7 + 36.7 \log_{10}(d_{\mathrm{p}}[\mathrm{km}])$ dB
Shadowing standard deviation	8 dB (outdoor), 10 dB (indoor)
Wall penetration loss	20 dB
Macro eNB antenna pattern	$A_{\mathrm{H}}(\theta) = -\min\left[12\left(\frac{\theta}{\theta_{3\,\mathrm{dB}}}\right)^2, A_{\mathrm{m}}\right]$ $\theta_{3\,\mathrm{dB}} = 70°$ and $A_{\mathrm{m}} = 20$ dB
Pico eNB antenna	Omnidirectional
Antenna gain BS	14 dBi (eNB), 5 dBi (pico eNB)
Antenna gain UE	0 dBi (MUE), 0 dBi (PUE)
UE power class	23 dBm (MUE), 23 dBm (PUE)
Thermal noise density	−174 dBm/Hz
Number of pico eNBs	1–4 pico eNBs/sector
Number of UEs (initial setup)	10 MUEs/sector, 2 PUEs/pico eNB
Min. distance MUE-macro eNB	35 m
Min. distance PUE-pico eNB	10 m
System/RB bandwidth	10 MHz (System), 180 kHz (RB)
Number of available RBs	50
Carrier frequency	2 GHz
Number of network topologies	500 topologies
Traffic model	Full buffer

The simulation parameters and values are listed in Table I, which are in accordance with the 3GPP LTE simulation assumptions [2], [3]. With respect to the strategy space, each UE transmitter utilizes 4 RBs ($L = 4$) for transmission and

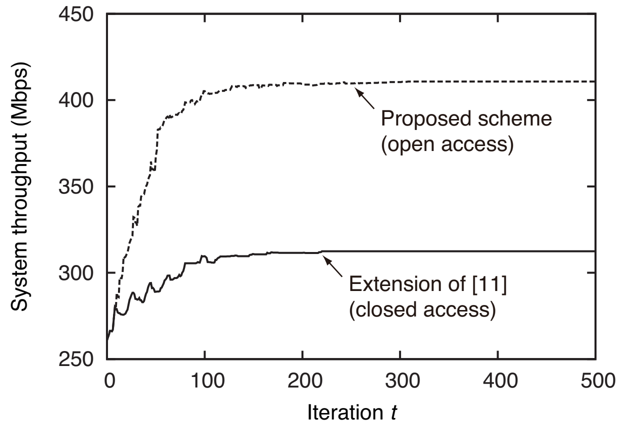

Fig. 3. Convergence of system throughput (4 pico eNBs/sector).

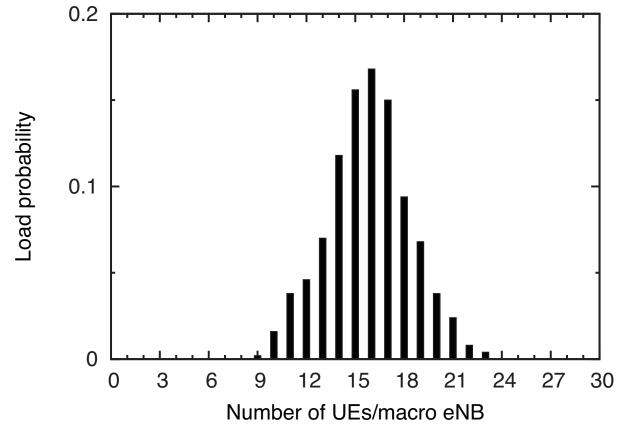

Fig. 4. Histogram of macro eNB load (4 pico eNBs/sector).

it is assumed that the total transmit power in each UE is divided equally among the selected RBs. For comparison, we consider a random allocation scheme and an extension of the adaptive channel allocation based on potential game [11]. In the extension of scheme in [11], the utility function consists of two terms as in the first two terms of (4), and thus support multiple RBs for transmission in closed access configuration. Performance statistics are collected from three sectors of the central macrocell, while the other sectors of different cell sites are considered only as interference contributors.

Fig. 3 shows the convergence of system throughput of the proposed scheme and the extension of the scheme in [11]. In the proposed self-organization scheme, each UE sequentially executes the algorithm shown in Fig. 2. At the final phase of the algorithm, the UE selects the most appropriate strategy of eNB and subset of RBs, and this eventually improves the system throughput. After some iteration steps, a steady state condition known as the Nash equilibrium is reached. At the convergence point, the load probability of macro eNBs can be observed as shown in Fig. 4. We can see from Fig. 4 that the proposed scheme reduces the load of macro eNBs from their initial load (30 UEs/macro eNB) by allowing the MUE for making a handoff to pico eNB.

Figs. 5 and 6 show the average MUE and PUE throughput for different number of pico eNB/sector; the user throughput was calculated based on an attenuated and truncated Shannon bound method for uplink case [13]. From Fig. 5, we see that increasing the number of pico eNBs will benefit the MUEs because more eNBs are available for handoff purpose. As a consequence, there is a slight loss of the PUE throughput of the proposed scheme compared to the extension of scheme in [11] as shown in Fig. 6. Moreover, the random allocation scheme achieves lower throughput performance of MUEs and PUEs compared to the other schemes.

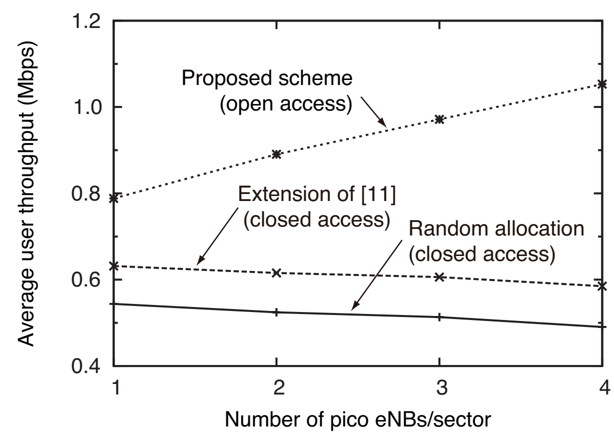

Fig. 5. Average macro UE throughput.

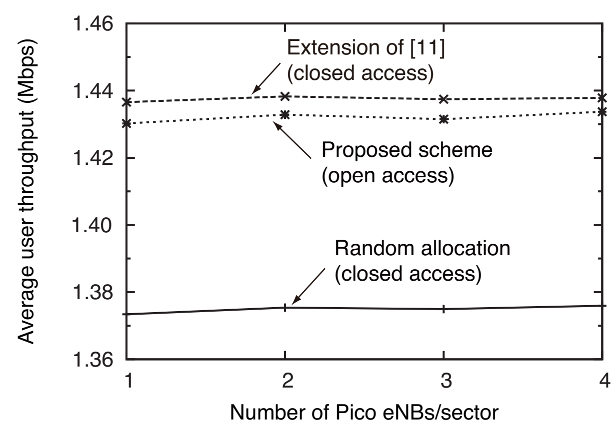

Fig. 6. Average pico UE throughput.

V. Conclusion

In this paper, we have proposed a self-organization scheme for uplink transmission in heterogeneous network. In the proposed scheme, each mobile user attempts to select the most appropriate base station and resource blocks in a decentralized manner in order to mitigate the cross- and co-tier interference, and improve the system throughput. The proposed self-organization scheme is modeled as a potential game which guarantees to converge to a Nash equilibrium. The simulation results show that the proposed scheme improves the uplink system throughput of the heterogeneous network with a slight loss of the picocell performance.

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APPENDIX

Proof: The potential function $P(s_i, \boldsymbol{s}_{-i})$ defined in (5) can be decomposed into two parts as follows:

$$P(s_i, \boldsymbol{s}_{-i}) = P^{(1)}(s_i, \boldsymbol{s}_{-i}) + P^{(2)}(s_i, \boldsymbol{s}_{-i}),$$

where

$$\begin{aligned} &P^{(1)}(s_i, \boldsymbol{s}_{-i}) \\ &= \sum_{i=1}^{N}\sum_{x=0}^{L-1}\sum_{y=0}^{L-1}\left(-\frac{1}{2}\sum_{j=1, j\neq i}^{N} G_j^{b_i} p_j^{k_j^{(y)}} \delta_{k_i^{(x)} k_j^{(y)}} - \frac{1}{2}\sum_{j=1, j\neq i}^{N} G_i^{b_j} p_i^{k_i^{(x)}} \delta_{k_j^{(y)} k_i^{(x)}}\right), \end{aligned}$$

$$P^{(2)}(s_i, \boldsymbol{s}_{-i}) = \sum_{i=1}^{N}\sum_{x=0}^{L-1}\left(G_i^{b_i}\, p_i^{k_i^{(x)}}\right).$$

Here, $P^{(1)}(s_i, \boldsymbol{s}_{-i})$ can be derived as

$$\begin{aligned} &P^{(1)}(s_i, \boldsymbol{s}_{-i}) \\ &= \sum_{x=0}^{L-1}\sum_{y=0}^{L-1}\Bigg[-\frac{1}{2}\sum_{j=1, j\neq i}^{N} G_j^{b_i} p_j^{k_j^{(y)}} \delta_{k_i^{(x)} k_j^{(y)}} - \frac{1}{2}\sum_{j=1, j\neq i}^{N} G_i^{b_j} p_i^{k_i^{(x)}} \delta_{k_j^{(y)} k_i^{(x)}} \\ &\quad + \sum_{l=1, l\neq i}^{N}\left(-\frac{1}{2}\, G_i^{b_l} p_i^{k_i^{(x)}} \delta_{k_l^{(y)} k_i^{(x)}} - \frac{1}{2}\, G_l^{b_i} p_l^{k_l^{(y)}} \delta_{k_i^{(x)} k_l^{(y)}}\right) \\ &\quad + \sum_{l=1, l\neq i}^{N}\left(-\frac{1}{2}\sum_{j=1, j\neq i, j\neq l}^{N} G_j^{b_l} p_j^{k_j^{(y)}} \delta_{k_l^{(x)} k_j^{(y)}} - \frac{1}{2}\sum_{j=1, j\neq i, j\neq l}^{N} G_l^{b_j} p_l^{k_l^{(x)}} \delta_{k_j^{(y)} k_l^{(x)}}\right)\Bigg]. \end{aligned}$$

$$\begin{aligned} \text{Let } Q^{(1)}(\boldsymbol{s}_{-i}) = \sum_{x=0}^{L-1}\sum_{y=0}^{L-1}\sum_{l=1, l\neq i}^{N}\Bigg(&-\frac{1}{2}\sum_{j=1, j\neq i, j\neq l}^{N} G_j^{b_l} p_j^{k_j^{(y)}} \delta_{k_l^{(x)} k_j^{(y)}} \\ &- \frac{1}{2}\sum_{j=1, j\neq i, j\neq l}^{N} G_l^{b_j} p_l^{k_l^{(x)}} \delta_{k_j^{(y)} k_l^{(x)}}\Bigg). \end{aligned}$$

Then, by substituting l with j, $P^{(1)}(s_i, \boldsymbol{s}_{-i})$ can be decomposed as

$$\begin{aligned} &P^{(1)}(s_i, \boldsymbol{s}_{-i}) \\ &= \sum_{x=0}^{L-1}\sum_{y=0}^{L-1}\left(-\sum_{j=1, j\neq i}^{N} G_j^{b_i} p_j^{k_j^{(y)}} \delta_{k_i^{(x)} k_j^{(y)}} - \sum_{j=1, j\neq i}^{N} G_i^{b_j} p_i^{k_i^{(x)}} \delta_{k_j^{(y)} k_i^{(x)}}\right) + Q^{(1)}(\boldsymbol{s}_{-i}). \end{aligned}$$

Next, $P^{(2)}(s_i, \boldsymbol{s}_{-i})$ can be derived as

$$P^{(2)}(s_i, \boldsymbol{s}_{-i}) = \sum_{x=0}^{L-1}\left(G_i^{b_i} p_i^{k_i^{(x)}} + \sum_{l=1, l\neq i}^{N} G_l^{b_l} p_l^{k_l^{(x)}}\right).$$

$$\text{Let } Q^{(2)}(\boldsymbol{s}_{-i}) = \sum_{x=0}^{L-1}\left(\sum_{l=1, l\neq i}^{N} G_l^{b_l} p_l^{k_l^{(x)}}\right).$$

Then $P^{(2)}(s_i, \boldsymbol{s}_{-i})$ can be decomposed as

$$P^{(2)}(s_i, \boldsymbol{s}_{-i}) = \sum_{x=0}^{L-1}\left(G_i^{b_i} p_i^{k_i^{(x)}}\right) + Q^{(2)}(\boldsymbol{s}_{-i}).$$

The function $Q(\boldsymbol{s}_{-i})$ corresponding to the strategy of the other players, $\boldsymbol{s}_{-i}$, can be expressed as

$$Q(\boldsymbol{s}_{-i}) = Q^{(1)}(\boldsymbol{s}_{-i}) + Q^{(2)}(\boldsymbol{s}_{-i}).$$

If player i changes its strategy from s_i to s_i', then we obtain

$$P(s_i', \boldsymbol{s}_{-i}) = u_i(s_i', \boldsymbol{s}_{-i}) + Q(\boldsymbol{s}_{-i}).$$

Consequently,

$$\begin{aligned} &P(s_i', \boldsymbol{s}_{-i}) - P(s_i, \boldsymbol{s}_{-i}) \\ &\quad = (u_i(s_i', \boldsymbol{s}_{-i}) + Q(\boldsymbol{s}_{-i})) - (u_i(s_i, \boldsymbol{s}_{-i}) + Q(\boldsymbol{s}_{-i})) \\ &\quad = u_i(s_i', \boldsymbol{s}_{-i}) - u_i(s_i, \boldsymbol{s}_{-i}). \end{aligned}$$

This proves that the proposed game is an exact potential game with a potential function P.

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