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Convergence analysis of interference-aware channel segregation

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Abstract: Our recently proposed interference-aware channel segregation based dynamic channel assignment (IACS-DCA) forms a channel reuse pattern with low co-channel interference (CCI) in a distributed manner. It has been shown by numerical computation that IACS-DCA forms a stable channel reuse pattern. In this paper, we provide convergence analysis of IACS-DCA. The existence of convergent point of channel reuse pattern and the convergence performance of IACS-DCA are discussed.

Keywords: dynamic channel assignment, co-channel interference, game theory, potential game

Classification: Wireless Communication Technologies

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1 Introduction

The number of available channels is limited in wireless networks. Since the CCI limits the network capacity, it is necessary to spatially reuse the channels so as to minimize the CCI in a network. Recently, we proposed IACS-DCA [1, 2]. It has been shown by numerical computation that IACS-DCA forms a stable channel reuse pattern with low CCI. In this paper, we provide theoretical analysis of the convergence of IACS-DCA by applying game theory. We formulate the behavior of IACS-DCA as the non-cooperative strategic form game, and then, clarify that Nash equilibrium (NE), i.e., convergent point of channel reuse pattern, exists in the formulated game. The convergence performance of IACS-DCA is evaluated by numerical computation.

2 Network model

Fig. 1 illustrates the network model assumed in this paper. Each access point (AP) is located at the center of each rectangular cell and the number of APs is $A_{all} = X \times Y$. The m-th ($m = 1 \sim A_{all}$) AP is represented as AP(m). The distance between adjacent APs is used as the reference distance R. The number of available channels is assumed to be N_{ch}. Each AP periodically measures the CCI powers on all available channels according to IACS-DCA [1, 2]. It has been reported [3] that the fading between stationary APs can vary due to movement of people in indoor wireless system. Therefore, in this paper, time-varying fading is considered between APs. Note that only the CCI between APs is considered in this paper.

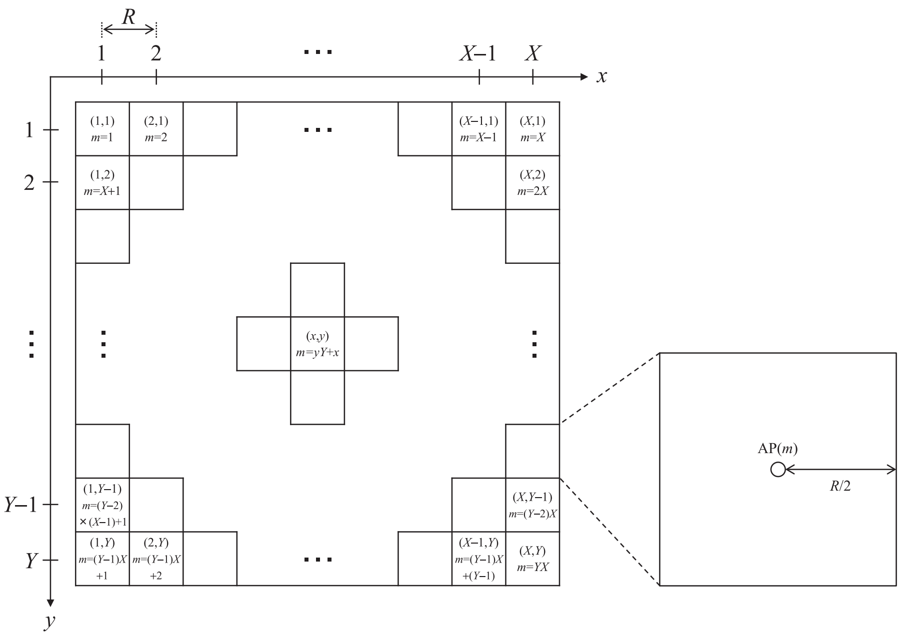

Fig. 1. Network model.

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3 Convergence analysis of IACS-DCA

3.1 Overview of IACS-DCA [1, 2]

We describe the principle of IACS-DCA as follows. Using IACS-DCA, each AP is designed to periodically measure the instantaneous CCI powers and to compute the average CCI powers on all available channels. Then, the channel-priority table is updated in which the channels are listed in ascending order of the average CCI power. The channel with the lowest average CCI power is selected.

In this paper, discrete time normalized by the CCI measurement time interval is used. Assuming the interference-limited condition, the instantaneous CCI power $I^{(c)}_{\mathrm{AP}(m)}(t)$ measured at AP(m) on the c-th channel ($c = 1{\sim}N_{ch}$) at CCI measurement time t ($t \geq 1$) is represented as

$$I^{(c)}_{\mathrm{AP}(m)}(t) = \left| \sum_{\substack{i=1,\\ i\neq m}}^{A_{all}} \sqrt{p_{tx}} \sqrt{r^{-\alpha}_{\mathrm{AP}(i),\mathrm{AP}(m)} \eta_{\mathrm{AP}(i),\mathrm{AP}(m)}} h^{(c)}_{\mathrm{AP}(i),\mathrm{AP}(m)}(t) \delta(c_{\mathrm{AP}(i)}(t), c) \right|^2, \quad (1)$$

where $p_{tx} = P_{tx}R^{-\alpha}$ is the normalized transmit power of AP and is the same for all APs with α being path-loss exponent. $r_{\mathrm{AP}(i),\mathrm{AP}(m)}$ and $\eta_{\mathrm{AP}(i),\mathrm{AP}(m)}$ are the normalized distance and the shadowing loss between AP(i) and AP(m), respectively. $h^{(c)}_{\mathrm{AP}(i),\mathrm{AP}(m)}(t)$ is the time-varying complex-valued fading gain between AP(i) and AP(m) at time t on the c-th channel, where $E[|h^{(c)}_{\mathrm{AP}(i),\mathrm{AP}(m)}(t)|^2] = 1$ ($E[.]$ denotes the ensemble average operation). $c_{\mathrm{AP}(i)}(t)$ represents the channel used by AP(i) at time t and $\delta(c_{\mathrm{AP}(i)}(t), c)$ is the function that gives 1 when AP(i) uses c-th channel at time t, otherwise it gives 0.

In our study [1, 2], the first order filtering is used to compute the average CCI power. The average CCI power $\bar{I}^{(c)}_{\mathrm{AP}(m)}(t)$ measured at AP(m) on the c-th channel at time t is given as

$$\bar{I}^{(c)}_{\mathrm{AP}(m)}(t) = \begin{cases} (1-\beta) I^{(c)}_{\mathrm{AP}(m)}(t) + \beta \bar{I}^{(c)}_{\mathrm{AP}(m)}(t-1) & (t \geq 1) \\ 0 & (t = 0) \end{cases}, \quad (2)$$

where β ($0 < \beta < 1$) denotes the forgetting factor. Then, AP selects the channel with the lowest average CCI power as

$$c_{\mathrm{AP}(m)}(t) = \arg\min_{c\in[1,N_{ch}]} \{\bar{I}^{(c)}_{\mathrm{AP}(m)}(t)\}. \quad (3)$$

After channel selection, each AP continues to use the selected channel until the next channel-priority table updating time.

3.2 Theoretical analysis of the convergence of IACS-DCA

In this paper, we provide theoretical analysis of the convergence of IACS-DCA by applying the game theory [4]. First, we formulate the IACS-DCA behavior as the non-cooperative strategic form game as

$$G := (M, \{C_{\mathrm{AP}(m)}\}_{m\in M}, \{u_{\mathrm{AP}(m)}\}_{m\in M}), \quad (4)$$

where $M = \{1, 2, \ldots, A_{all}\}$ denotes the set of players, i.e., APs. The strategy set for each AP $C_{\mathrm{AP}(m)}$ is the set of available channels and is represented as

$$C_{\mathrm{AP}(m)} = \{1, 2, \ldots, N_{ch}\}, \quad \forall m \in M. \quad (5)$$

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$u_{\mathrm{AP}(m)}$ is the utility function of each AP. In a strategic form game, each player selects a strategy so as to maximize its utility. On the other hand, each AP selects the channel with the lowest average CCI power in IACS-DCA. Therefore, $u_{\mathrm{AP}(m)}$ is set as the negative value of average CCI power and is represented as

$$u_{\mathrm{AP}(m)}(c_{\mathrm{AP}(m)}(t), \boldsymbol{c}_{-\mathrm{AP}(m)}(t)) = -\{(1-\beta)I_{\mathrm{AP}(m)}^{(c_{\mathrm{AP}(m)}(t))}(t) + \beta\bar{I}_{\mathrm{AP}(m)}^{(c_{\mathrm{AP}(m)}(t))}(t-1)\},\ \forall m \in M, \tag{6}$$

where $\boldsymbol{c}_{-\mathrm{AP}(m)}(t) = (c_{\mathrm{AP}(1)}(t), c_{\mathrm{AP}(2)}(t), \ldots, c_{\mathrm{AP}(m-1)}(t), c_{\mathrm{AP}(m+1)}(t), \ldots, c_{\mathrm{AP}(A_{all})}(t))$ is the channels selected by all of APs except for AP(m) at time t and $(c_{\mathrm{AP}(m)}(t), \boldsymbol{c}_{-\mathrm{AP}(m)}(t)) = (c_{\mathrm{AP}(1)}(t), c_{\mathrm{AP}(2)}(t), \ldots, c_{\mathrm{AP}(m-1)}(t), c_{\mathrm{AP}(m)}(t), c_{\mathrm{AP}(m+1)}(t), \ldots, c_{\mathrm{AP}(A_{all})}(t))$ represents the channels selected by all of APs at time t.

IACS-DCA forms a stable channel reuse pattern when the forgetting factor β is close to 1, e.g. $\beta = 0.999$ [2]. From Eqs. (1) and (2), the average CCI power measured at AP(m) on the c-th channel at the time $t = T$ can be represented as

$$\begin{aligned}
&\bar{I}_{\mathrm{AP}(m)}^{(c)}(t=T) \\
&= (1-\beta)\sum_{t=1}^{T}\beta^{T-t}I_{\mathrm{AP}(m)}^{(c)}(t) \\
&= (1-\beta)\sum_{t=1}^{T}\left\{\beta^{T-t}\left|\sum_{\substack{i=1,\\ i\neq m}}^{A_{all}}\sqrt{p_{tx}}\sqrt{r_{\mathrm{AP}(i),\mathrm{AP}(m)}^{-\alpha}\eta_{\mathrm{AP}(i),\mathrm{AP}(m)}}h_{\mathrm{AP}(i),\mathrm{AP}(m)}^{(c)}(t)\delta(c_{\mathrm{AP}(i)}(t),c)\right|^2\right\}
\end{aligned}. \tag{7}$$

After sufficient CCI averaging (i.e., T is sufficiently large), Eq. (7) can be approximated as

$$\begin{aligned}
&\bar{I}_{\mathrm{AP}(m)}^{(c)}(t=T) \\
&\approx (1-\beta)\cdot E\left[\left|\sum_{\substack{i=1,\\ i\neq m}}^{A_{all}}\sqrt{p_{tx}}\sqrt{r_{\mathrm{AP}(i),\mathrm{AP}(m)}^{-\alpha}\eta_{\mathrm{AP}(i),\mathrm{AP}(m)}}h_{\mathrm{AP}(i),\mathrm{AP}(m)}^{(c)}(t)\delta(c_{\mathrm{AP}(i)}(t),c)\right|^2\right], \\
&= (1-\beta)\left[p_{tx}\sum_{\substack{i=1,\\ i\neq m}}^{A_{all}}r_{\mathrm{AP}(i),\mathrm{AP}(m)}^{-\alpha}\eta_{\mathrm{AP}(i),\mathrm{AP}(m)}\left\{\sum_{t=1}^{T}\delta(c_{\mathrm{AP}(i)}(t),c)\right\}\right]
\end{aligned} \tag{8}$$

where $\beta^{T-t} \approx 1$ is assumed. Note that the approximation of $\beta^{T-t} \approx 1$ is satisfied if β is very close to 1, e.g., $\beta = 0.999$.

On the basis of Eq. (8), we transform the game G into the new game $\tilde{G}$ denoted as

$$\tilde{G} := (M, \{C_{\mathrm{AP}(m)}\}_{m\in M}, \{\tilde{u}_{\mathrm{AP}(m)}\}_{m\in M}), \tag{9}$$

where $\tilde{u}_{\mathrm{AP}(m)}$ is set as the negative value of the approximated average CCI power and is represented as

$$\begin{aligned}
&\tilde{u}_{\mathrm{AP}(m)}(c_{\mathrm{AP}(m)}(T), \boldsymbol{c}_{-\mathrm{AP}(m)}(T)) \\
&= -(1-\beta)\left[p_{tx}\sum_{\substack{i=1,\\ i\neq m}}^{A_{all}}r_{\mathrm{AP}(i),\mathrm{AP}(m)}^{-\alpha}\eta_{\mathrm{AP}(i),\mathrm{AP}(m)}\left\{\sum_{t=1}^{T}\delta(c_{\mathrm{AP}(i)}(t),c_{\mathrm{AP}(m)}(t))\right\}\right],\ \forall m \in M
\end{aligned}. \tag{10}$$

Regarding game $\tilde{G}$, we obtain the following theorem.

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Theorem 1. The non-cooperative strategic form game $\tilde{G}$ is an exact potential game (EPG) [5].

Proof: We construct a potential function as

$$f(c_{\mathrm{AP}(m)}(T), \boldsymbol{c}_{-\mathrm{AP}(m)}(T)) = -\frac{1}{2} p_{tx}(1-\beta) \sum_{i=1}^{A_{all}} \sum_{\substack{j=1,\\ j\neq i}}^{A_{all}} \left[r_{\mathrm{AP}(i),\mathrm{AP}(j)}^{-\alpha} \eta_{\mathrm{AP}(i),\mathrm{AP}(j)} \left\{ \sum_{t=1}^{T} \delta(c_{\mathrm{AP}(i)}(t), c_{\mathrm{AP}(j)}(t)) \right\} \right]. \quad (11)$$

Suppose that an arbitrary AP(m) unilaterally changes its channel from $c_{\mathrm{AP}(m)}(T)$ to $c'_{\mathrm{AP}(m)}(T)$. The difference in individual utilities caused by this change is given as

$$\tilde{u}_{\mathrm{AP}(m)}(c_{\mathrm{AP}(m)}(T), \boldsymbol{c}_{-\mathrm{AP}(m)}(T)) - \tilde{u}_{\mathrm{AP}(m)}(c'_{\mathrm{AP}(m)}(T), \boldsymbol{c}_{-\mathrm{AP}(m)}(T)) = -(1-\beta) \left[p_{tx} \sum_{\substack{i=1,\\ i\neq m}}^{A_{all}} r_{\mathrm{AP}(i),\mathrm{AP}(m)}^{-\alpha} \eta_{\mathrm{AP}(i),\mathrm{AP}(m)} \{ \delta(c_{\mathrm{AP}(i)}(T), c_{\mathrm{AP}(m)}(T)) - \delta(c_{\mathrm{AP}(i)}(T), c'_{\mathrm{AP}(m)}(T)) \} \right]. \quad (12)$$

On the other hand, the potential function can be transformed as

$$\begin{aligned} f(c_{\mathrm{AP}(m)}(T), \boldsymbol{c}_{-\mathrm{AP}(m)}(T)) &= -p_{tx}(1-\beta) \sum_{\substack{i=1,\\ i\neq m}}^{A_{all}} \left[r_{\mathrm{AP}(i),\mathrm{AP}(m)}^{-\alpha} \eta_{\mathrm{AP}(i),\mathrm{AP}(m)} \left\{ \sum_{t=1}^{T} \delta(c_{\mathrm{AP}(i)}(t), c_{\mathrm{AP}(m)}(t)) \right\} \right] \\ &\quad - \frac{1}{2} p_{tx}(1-\beta) \sum_{\substack{i=1,\\ i\neq m}}^{A_{all}} \sum_{\substack{j=1,\\ j\neq m,i}}^{A_{all}} \left[r_{\mathrm{AP}(i),\mathrm{AP}(j)}^{-\alpha} \eta_{\mathrm{AP}(i),\mathrm{AP}(j)} \left\{ \sum_{t=1}^{T} \delta(c_{\mathrm{AP}(i)}(t), c_{\mathrm{AP}(j)}(t)) \right\} \right] \end{aligned}, \quad (13)$$

where the propagation loss has the symmetric property according to the network model as

$$r_{\mathrm{AP}(m),\mathrm{AP}(i)}^{-\alpha} \eta_{\mathrm{AP}(m),\mathrm{AP}(i)} h_{\mathrm{AP}(m),\mathrm{AP}(i)}^{(c)}(t) = r_{\mathrm{AP}(i),\mathrm{AP}(m)}^{-\alpha} \eta_{\mathrm{AP}(i),\mathrm{AP}(m)} h_{\mathrm{AP}(i),\mathrm{AP}(m)}^{(c)}(t). \quad (14)$$

Since the second term of Eq. (13) is independent from the channel of AP(m), we obtain:

$$\begin{aligned} & f_{\mathrm{AP}(m)}(c_{\mathrm{AP}(m)}(T), \boldsymbol{c}_{-\mathrm{AP}(m)}(T)) - f_{\mathrm{AP}(m)}(c'_{\mathrm{AP}(m)}(T), \boldsymbol{c}_{-\mathrm{AP}(m)}(T)) \\ &= -(1-\beta) \left[p_{tx} \sum_{\substack{i=1,\\ i\neq m}}^{A_{all}} r_{\mathrm{AP}(i),\mathrm{AP}(m)}^{-\alpha} \eta_{\mathrm{AP}(i),\mathrm{AP}(m)} \{ \delta(c_{\mathrm{AP}(i)}(T), c_{\mathrm{AP}(m)}(T)) - \delta(c_{\mathrm{AP}(i)}(T), c'_{\mathrm{AP}(m)}(T)) \} \right]. \\ &= \tilde{u}_{\mathrm{AP}(m)}(c_{\mathrm{AP}(m)}(T), \boldsymbol{c}_{-\mathrm{AP}(m)}(T)) - \tilde{u}_{\mathrm{AP}(m)}(c'_{\mathrm{AP}(m)}(T), \boldsymbol{c}_{-\mathrm{AP}(m)}(T)) \end{aligned} \quad (15)$$

Eq. (15) means that the difference in individual utilities achieved by each AP when changing unilaterally its channel has the same value as the difference in values of the potential function. Thus, the game $\tilde{G}$ is an EPG by the definition given in [5]. ■

It is known that if a non-cooperative strategic form game is an EPG with a finite set of available strategies for all players, the dynamics that each player sequentially changes its strategy to improve own utility are guaranteed to converge to NE in a finite iteration [5]. Consequently, IACS-DCA in which each AP selects the channel with the lowest average CCI power have the convergent point of channel reuse pattern on the following assumptions:

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(A) CCI is sufficiently averaged.
(B) Transmit power is the same for all APs.
(C) Each AP sequentially selects the channel with the lowest average CCI power.

4 Numerical evaluation

We evaluate the convergence performance of IACS-DCA and verify the validity of the theoretical analysis by numerical computation. We assume a network with $A_{all} = 5 \times 5 = 25$, $N_{ch} = 3$, and the interference-limited condition. The same normalized transmit power p_{tx} is assumed for all APs. The propagation channel is assumed to be characterized by distance-dependent path loss with path-loss exponent $\alpha = 3.5$, shadowing loss following a log-normal distribution with standard deviation $\sigma = 5.0\,\text{dB}$, and frequency-nonselective Rayleigh fading. It is assumed that the fading between each AP is uncorrelated.

Fig. 2 illustrates the flowchart of one-trial numerical computation. In the m-th step ($m = 1\sim25$), AP(m) measures the instantaneous CCI powers on all available channels, calculates the average CCI powers by Eq. (2), and selects the channel with the lowest average CCI power. Fading between APs is assumed to change every step. One round consists of 25 steps and is repeated until the channel reuse pattern converges. In this paper, when the channel reuse pattern is stationary during 5 rounds, it is determined that the channel reuse pattern has converged. The trial ends when the channel reuse pattern has converged or doesn't converge after 100 rounds. The numerical computation results are obtained by conducting 100,000 trials.

Fig. 3 shows the average number of rounds required for the channel reuse pattern converges and the probability that channel reuse pattern doesn't converge within 100 rounds as a function of β. It is seen from Fig. 3 that when small β is used, the channel reuse pattern doesn't converge in a high probability and the number of rounds required to converge is large. This is because the assumption (A)

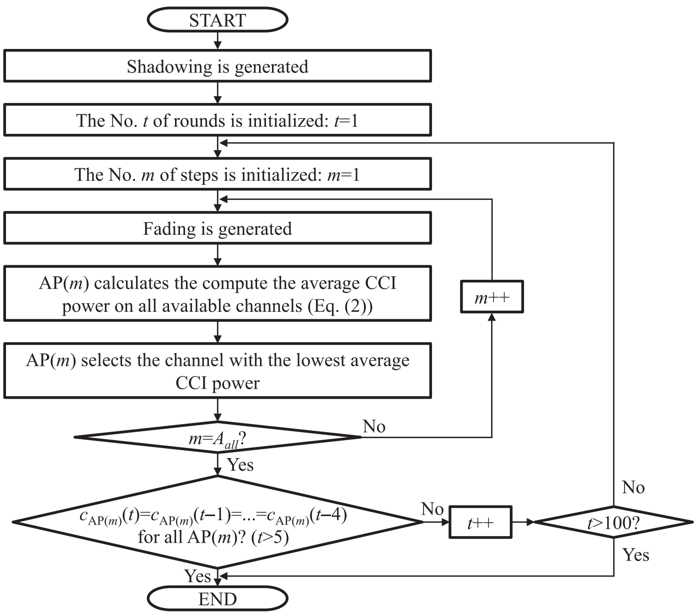

Fig. 2. Flowchart of one-trial numerical computation.

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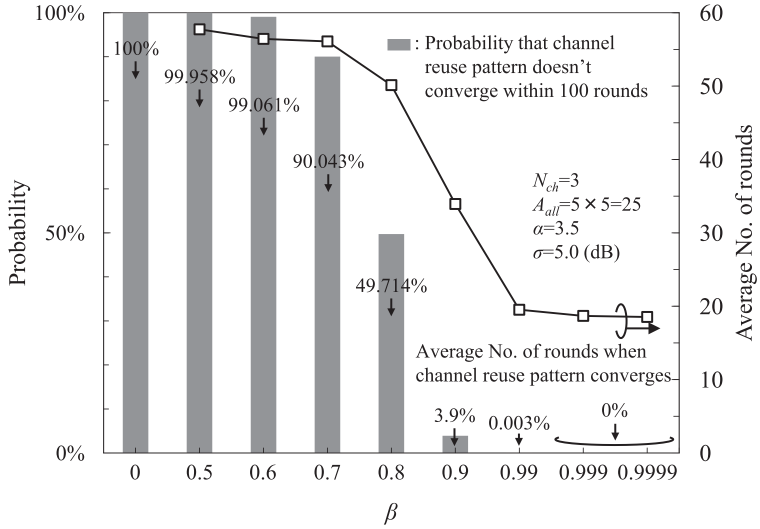

Fig. 3. Convergence performance of IACS-DCA.

is not satisfied and the convergence of IACS-DCA cannot be guaranteed when small β is used. It is seen from Fig. 3 that the probability that channel reuse pattern doesn't converge becomes lower as larger β is used. It is confirmed that the channel reuse pattern converges in all trials when $1 > \beta \geq 0.999$.

5 Conclusions

In this paper, we provided theoretical analysis of the convergence of IACS-DCA. The behavior of IACS-DCA was formulated as the non-cooperative strategic form game. We showed that the formulated game is the EPG and therefore, IACS-DCA in which each AP selects the channel with the lowest average CCI power has the convergent point of channel reuse pattern. We evaluated by numerical computation the convergence performance of IACS-DCA and showed that the channel reuse pattern converges if the assumptions (A)–(C) are satisfied.

From the analysis in this paper, each AP is required to sequentially select the channel with lowest average CCI power. However, sequential operation may require long period of time to converge when the number of APs is large. The AP operation which requires shorter period of time to converge while guaranteeing the convergence is an important practical issue. In addition, the evaluation of the tracking performance to the change of CCI environment is also left as an important future study.

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