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AP Connection Method for Maximizing Throughput Considering Moving User and Degree of Interference Based on Potential Game

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ABSTRACT For multi-transmission rate environments, access point (AP) connection methods have been proposed for maximizing system throughput, which is the throughput of an entire system, on the basis of the cooperative behavior of users. These methods derive optimal positions for the users' cooperative behavior, which means that new users move to improve the system throughput when connecting to an AP. However, conventional methods only focus on increasing the transmission rate of new users without regard to the performance impact on existing users. In addition, these methods do not account for co-channel or stacked frequency interference between users. In this paper, we propose a novel approach to access point connectivity which maximizes the system throughput by taking into account the interference between users and the initial position of all users. In addition, our proposed method can improve system throughput by about 6 % at most compared to previous methods.

INDEX TERMS AP connection method, throughput, interference, potential game, user moving, optimal position.

I. INTRODUCTION

ADVANCES in communication technology have increased the number of users of wireless terminal devices such as smartphones, tablets, and personal computers. Especially, public wireless LAN services have been widely deployed in cafes, offices, schools, and other public facilities as a result of the rapid spread of wireless LANs. In such environments, multiple users share the same access point (AP).

In general, the total throughput of an AP (system throughput) is reduced when one user requests a much lower transmission rate than other users in a multi transmission rate environment where each user has a different transmission rate [1]. To address this problem, AP connection methods for selecting an appropriate position in a multi-transmission rate environment have been proposed [1], [2], [3].

Previously, Miyata et al. [2] proposed an AP connection method to maximize system throughput based on users' cooperative behavior. Cooperative behavior means that the user moves to improve the system throughput. In [2], it is assumed that the user is moving, and the model changes the transmission rate depending on the user's position. However, this study did not consider interference, even though users need to move to positions where interference is taken into consideration in order to improve system throughput. Here, interference refers to packet collisions between users.

An AP connection method that maximizes system throughput based on users' cooperative behavior and considers the interference between users has also been proposed [3]. However, this study assumed that there is always interference between users. In recent wireless LAN environments that are equipped with CSMA/CA, it is difficult to imagine a situation where there is always interference between users because CSMA/CA has the ability to control packet collisions [4]. Therefore, for a realistic analysis, it is necessary to regard to the degree of interference between users.

However, the limitation of these prior studies [2], [3] is that they only considered the transmission rates of a limited number of users rather than all users. To improve system throughput, the transmission rates of all users and interference need to be considered. Generally, there are fixed users in the previous studies, although there is a probability that some of the fixed users may be moving [5]. The performance of AP connection methods should be evaluated assuming that some of the fixed users also move.

In this paper, we aim to solve these problems by modeling them using a potential game. In this way, we can find at least one optimal solution because we can make the incentives of all users a single function. In particular, we add the terms of probability of no packet collisions and probability of packet collisions to the system throughput equation used in previous work to take into account the degree of interference. We then propose an AP connection method that maximizes system throughput by extending the adaptive range of potential game players to all users instead of only a limited number of users. By extending the adaptive range of players in the potential game from some users to all, we can avoid the scenario where only one user's transmission rate is extremely low, thus preventing the loss of overall system performance.

The main contribution of this paper is the application of a potential game to facilitate the complex analysis of system throughput in wireless LAN environments, which depend on the user's position. Other contributions and differences between previous studies are as follows:

- Theoretical analysis close to real environments considering scenarios with and without interference.
- Proposed method for maximizing system throughput considering the initial positions of users connected to the same AP.
- Analysis of optimal user position that maximizes system throughput by using a potential game to take interference into account.

The remainder of this paper is organized as follows. Section II describes related work on AP connection methods, and Section III discusses the proposed method in detail, including the utility function. Section IV presents a numerical analysis, and Section V summarizes and discusses the limitation of this work.

II. RELATED WORK

In general, previous studies on wireless networks have aimed to improve system throughput, with a focus on AP connection methods. The approaches can generally be categorized into methods that connect to APs with user movement and those without user movement.

A. CONNECTION METHODS WITHOUT USER MOVEMENT

Among the methods of connecting to an AP without user movement, Raschellà et al. proposed a method for selecting the appropriate AP by focusing on each user application to increase throughput [6]. In addition, Raschellà et al. theoretically prove the existence of a solution by using a potential game [7]. However, this method does not consider user movement [6], [7]. Thus, if a new user arrives at a position far from the AP, the user must connect to the AP at the arrival position. This results in a low transmission rate, which causes performance anomalies. Liu et al. proposed a method which connects to an AP considering the transmission rates of each user in a multi-rate environment, not only RSSI [8]. However, the throughput used in this method assumes no packet collisions, i.e., no interference, between users. Thus, this method differs from a real WLAN environment where multiple users are connected. Moreover, Mohsenivatani et al. solved the power allocation problem by using deep learning to increase throughput [9]. The contribution of this study is their use of deep learning to solve the power allocation problem, which is an NP-hard problem. However, they only performed the analysis in one assumed environment and did not thoroughly analyze when the environment was changed. Moreover, deep learning is computationally intensive.

In contrast to the above previous studies, our study aims to improve throughput by focusing on user mobility, which is a cost-effective approach.

B. CONNECTION METHODS WITH USER MOVEMENT

Methods of connecting to an AP with user movement can be divided into two types: indirect connection between the AP and a new user via relaying terminals such as other users or drones, and direct connection between an AP and a new user.

Regarding indirect connection methods, Yanai et al. optimized the flight paths of drones in a wireless relay network [10], which resulted in shorter transmission delays. However, this method does not consider the interference or signal strength between drones. Xie and Murase derived the optimal position between users in an ad hoc network in consideration of the interference between each user [11]. Furthermore, Anjiki and Murase considered dynamic routing according to user mobility in ad hoc networks [12]. As a result, appropriate user selection and user positioning were analyzed to improve throughput. However, these methods are multi-hop and assume that all nodes can move, whereas WLANs have the limitation of a fixed AP.

Direct connection methods include Miyata et al.'s method, which improves system throughput on the basis of users' cooperative behavior [2], [13], and Yamori and Tanaka's method, which improves system throughput by encouraging them to select other APs by encouraging users to move [14]. However, these methods do not consider interference between users.

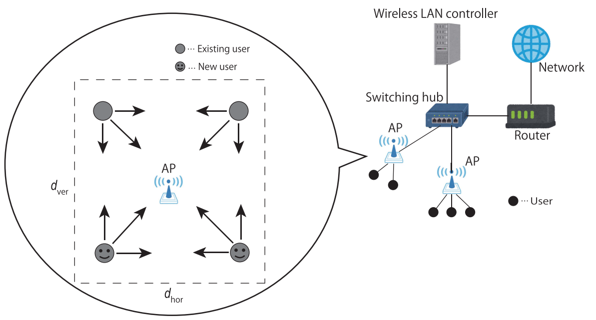


FIGURE 1. System model.

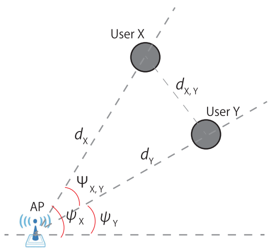


FIGURE 2. User position model.

Previous studies have suggested that user movement can improve throughput in a wireless LAN environment. However, these studies do not address the possibility that user movement can also increase interference.

In summary, there is no comprehensive system throughput analysis that considers both user movement and interference between users in a wireless network environment.

III. PROPOSED METHOD

A. ASSUMED ENVIRONMENT

In this study, the proposed method is considered as a potential option for Wi-Fi services in classrooms and libraries due to its location-free characteristics and low human traffic. The Wi-Fi system calculates the optimal user position based on the users' locations to enhance throughput and encourages users to take cooperative action. Users exhibit cooperative behavior with the system, motivated by the desire to increase their own throughput.

Fig. 1 shows the assumed system environment for our proposed method. Here, all users are assumed to arrive in the area $d_{\mathrm{ver}} \times d_{\mathrm{hor}}$, where d_{ver} is the vertical length and d_{hor} is the horizontal length of the area. Users are managed in a centralized manner by the wireless LAN controller for the AP, and when they arrive at this area, information such as the position of all users connected to the same AP and the distance between APs is exchanged [15]. Then, on the basis of the information, the optimal user position is calculated and moved using a potential game.

In this paper, we assume that a user requesting a connection arrives at an AP, and that some users are already connected to the AP. In our proposed system, the AP calculates and selects the users with the highest system throughput when they arrive at the AP. In addition, the AP prompts the selected user to move on. The user will cooperate with the AP, and this is called the user's cooperative behavior. The motivation for the users is the increased throughput of their own terminal, which they gain through the cooperative behavior. Our AP connection method proposed in this paper improves system throughput on the basis of the user's cooperative behavior in a multi-transmission rate environment.

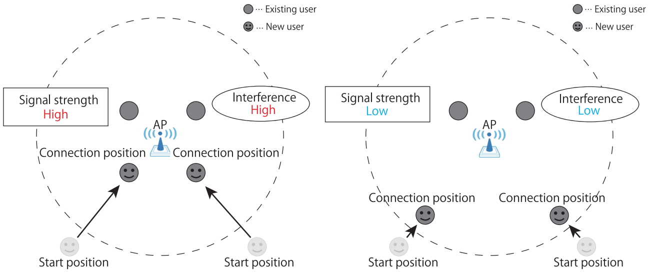
We consider an IEEE802.11 WLAN environment as the network setting. It is assumed that all users will consistently request traffic in the uplink direction. However, to clarify the degree of interference and the signal strength between one AP and the users connected to it, we first consider the case of a single AP in this paper. Therefore, we only consider interference received from users connected to the same AP. In other words, the interference in this paper is the effect of packet collisions between users connected to the same AP.

The probability of packet collisions is generally small when the number of users is small because the CSMA/CA is taken in the IEEE802.11 WLAN environment. However, when there are hidden terminals, the probability of packet collisions substantially increases, which greatly affects the throughput obtained by users [16], [17], [18]. This hidden terminal problem is also an important issue in real environments [16], [17], [18]. Therefore, in this paper we assume the case in which there are many hidden terminals in this paper.

In this network environment, each user always requests traffic in one direction upstream, and we assume a multi-rate WLAN environment where the appropriate transmission rate is selected from multiple transmission rates. The transmission rate for each user is selected on the basis of the distance between the AP and the user and the interference from other users.

In a multi-transmission rate environment, the transmission rate is determined by the signal strength and the interference from other users. In addition, the signal strength and the interference are determined by the distance between the user and the AP. In other words, the signal strength and the interference are determined by each user's position. Therefore, the positions of users is important in determining the transmission rate for each user. Each user's position can be determined by the distance and angle from the AP. Fig. 2 shows the user's position model. In this paper, we denote a user as X. Note that the distance between a user X - AP is d_X and the angle between user X - the horizontal line of AP is ψ_X, as shown in Fig. 2. Moreover, the position $\boldsymbol{d}_X$ of a user X can be expressed as $\boldsymbol{d}_X = (d_X, \psi_X)$. Specifically, let the position of a moving user X be $\boldsymbol{d}_X^{\mathrm{mov}}$. In this paper, there are users who move and those who do not move. Therefore, there are two types of user positions: before the user has moved and after the user has moved. Here, the user X position before moving is denoted as $\hat{\boldsymbol{d}}_X$, and the user X position after moving is denoted as $\tilde{\boldsymbol{d}}_X$.

In a multi-transmission rate environment, when multiple users connect to the same AP, the transmission rate is



(a) If the new user's connection position is close to the AP. **(b)** If the new user's connection position is far from the AP.

FIGURE 3. **Trade-off diagram between user-AP distance and interference between users.**

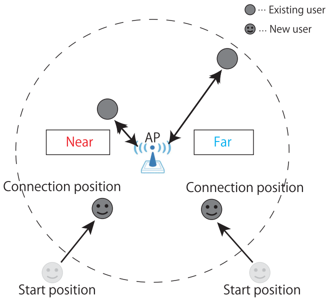


FIGURE 4. **Problem of the conventional method [3].**

determined by the distance d_X between the AP and a user X and the distance d_Y between the AP and the other user Y. If the distance d_X between the AP and a user X is short, the transmission rate will be high because the signal strength will be high. However, as shown Fig. 3(a), when users move closer to the AP in order to increase the signal strength, the distance d_Y between the AP and the other user Y becomes shorter. As a result, the transmission rate will be low because the interference is larger when the distance d_Y between the AP and the other user Y is shorter. Meanwhile, as shown Fig. 3(b), if the distance d_X between the AP and a user X is long in order to decrease the interference, the transmission rate will be low because the signal strength will be low. Thus, there is a trade-off between the distance d_X between an AP and a user X and the distance d_Y between the AP and the other user Y.

In the previous method [3], there are existing users who are already connected to the AP and new users who request a connection. This method overcomes the trade-off by moving the new users to the new location. However, as shown in Fig. 4, if one existing user connects close to the AP and another existing user connects far from the AP, there is a possibility that the system throughput will be low. This is because the previous method assumes that only new users move. Thus, even if a new user moves to the optimal position, as shown in Fig. 4, the transmission rate will be low because only one existing user is connected far from the AP. Therefore, in this paper, we solve this problem by including all users as players in the potential game, not only new users.

TABLE 1. **Notation for our method.**

Parameters	Description
$\mathcal{S}$	Set of players in game theory
a_i	Strategy of player i
u_i	Utility function for player i
$\mathcal{A}$	Direct product set of all players' strategies
$\boldsymbol{a_{-i}}$	Set of strategies for player j, $j \in \mathcal{S}$, $j \neq i$
$\mathscr{G}_{\text{pot}}$	Potential game
$\mathscr{G}_{\text{all mov}}$	All user movement game
a_i^*	Strategies that result in Nash equilibrium for player i
n	Moving user
$\mathcal{N}$	Set of moving users
m	Non-moving user
$\mathcal{M}$	Set of non-moving users
$\mathcal{L}$	Set of all users
$\boldsymbol{d}_X$	Position of user X
d_X	Distance between AP and user X
ψ_X	Angle between the horizontal line of AP and user X
$\boldsymbol{c}^{\text{mov}}$	Combination of selected moving users
R_X	Effective transmission rate for user X
θ	System throughput
W	Channel bandwidth
Z_X	Signal to noise ratio (SNR) for user X
Γ_X	Signal to interference and noise ratio (SINR) for user X
$P_{\text{collision}}^{\text{non}}$	Probability of non-collision
$P_{\text{collision}}$	Probability of collision
P_X^{receive}	Received power of an AP when a user X communicates
I_Y	Interference power from users except for user $Y \in \mathcal{L}$, $Y \neq X$
N_0	Background noise power
δ	SINR threshold
$P_{\text{AP}}^{\text{send}}$	Each user's transmit power
g	Antenna gain
$\tilde{d}_X^{\text{mov}}$	Distance between AP and user X after moving
α	Path loss exponent
$\tilde{\boldsymbol{d}}_i^{\text{mov}*}$	Optimal position of moving user i
$\hat{u}_i$	Intermediate utility function

B. MODELING BY GAME THEORY

The description of each parameter in the game theory model is shown in Table 1.

For wireless communication environments where multiple users exist and users must be considered, game theory is one of the most suitable theories to use for analysis [19], [20], [21]. In this paper, the user position that maximizes system throughput is determined using a potential game, which is one of the models of game theory. A feature of a potential game is that it has at least one solution [22], which is called the Nash equilibrium. By using this property, the system heuristically calculates combinations of user positions. A potential game consists of three elements: the players $\mathcal{S} = \{1, \ldots, S\}$, the strategy a_i of player i, and the utility function $u_i(\boldsymbol{a}) : \mathcal{A} \longmapsto \mathbb{R}$ of player i. Let $\mathbb{R}$ be a set of real numbers. In this paper, we model our method using the potential game $\mathscr{G}_{\text{pot}}$. Moreover, the potential game $\mathscr{G}_{\text{pot}}$ is denoted as all user movement game $\mathscr{G}_{\text{all mov}} := \{\mathcal{S}, \mathcal{A}, (u_i)_{i \in \mathcal{S}}\}$. Finally, the objective of this paper is to find the Nash equilibrium. Here, let strategies that result in Nash equilibria for the player i be a_i^*, and the Nash equilibrium be defined as in Eq. (1) [23].

$$u_i\left(a_i^*, \boldsymbol{a}_{-i}^*\right) \geq u_i\left(a_i', \boldsymbol{a}_{-i}^*\right), \forall a_i' \in \mathcal{A}, \forall i \in \mathcal{S}. \tag{1}$$

In modeling the potential game, we assume two types of users (moving and non-moving) to simplify the problem. The AP selects users to move and users not to move from all users connected to the AP. Let moving users be $n \in \{1, 2, \ldots, N\} = \mathcal{N}$, non-moving users be $m \in \{1, 2, \ldots, M\} = \mathcal{M}$, and the set of all users be $\mathcal{L} = \{1, 2, \ldots, L\}$. Moreover, we assume that combination of selected moving users is $\boldsymbol{c}^{\text{mov}} = (i, j),\ i, j \in \mathcal{L}$.

Adapting our method to the potential game, we assume that player $\mathcal{S}$ is a set of moving users $i \in \mathcal{N}$, strategy $\mathcal{A}$ is the distance d_i and direction ψ_i of the moving users. In other words, the strategy of our proposed method is to relocate the moving user to an arbitrary position. The utility function u_i is defined as in Eq. (2).

$$u_i(a_i, \boldsymbol{a}_{-i}) = \frac{1}{\sum_{n\in\mathcal{N}} \frac{1}{R_n(a_n, \boldsymbol{a}_{-n})} + \sum_{m\in\mathcal{M}} \frac{1}{R_m(a_i, \boldsymbol{a}_{-i})}}, \tag{2}$$

where R_n is the effective transmission rate obtained by a moving user and R_m is the effective transmission rate obtained by a non-moving user. Note that Eq. (2) can consider the throughput of moving user i. In the following, we explain why this equation represents the user's throughput.

We assume that each user's transmission link is saturated so that no single transmission link becomes the bottleneck. As a result, the total throughput (system throughput) for this transmission link can be expressed as the harmonic mean of each user's transmission rate [2], [11]. Thus, the system throughput θ, which is the sum of users' throughputs, is as follows,

$$\theta = \frac{N + M}{\sum_{n\in\mathcal{N}} \frac{1}{R_n(a_n, \boldsymbol{a}_{-n})} + \sum_{m\in\mathcal{M}} \frac{1}{R_m(a_i, \boldsymbol{a}_{-i})}}. \tag{3}$$

In particular, let the system throughput when a user X and a user Y move be θ_{XY}. In this paper, we assume that the communication standard is IEEE802.11g, so each user has an equal chance to communicate with the AP. Therefore, the system throughput divided by the number of users can be expressed as the throughput of each user. Moreover, by adjusting Eqs. (2), (3), they can be applied to other communication systems.

From Eqs. (2), (3), maximizing u_i is equivalent to maximizing θ. Thus, the objective of this paper can be achieved by maximizing the throughput of each user. In addition, Eq. (3), (21) are used as an evaluation basis.

Here, the effective transmission rate R_X for a user X can be expressed from Shannon's theorem as follows [24],

$$R_X = W \log_2 \{1 + \Gamma_X\}, \tag{4}$$

where W represents the channel bandwidth. Moreover, Γ_X is the signal to interference and noise power ratio (SINR), which is the ratio of a user X's own signal power to the interference power.

However, Shannon's theorem assumes that the effect of interference from other users is constant. Therefore, because we assume a wireless LAN environment in this paper, there are cases in which packet collisions do not occur due to the CSMA/CA. In other words, if packet collisions do not occur, we do not need to consider the effects of interference. Thus, by adapting Shannon's theorem to this paper, the effective transmission rate R_X for a user X can be expressed as follows,

$$\begin{aligned} R_X(a_i, \boldsymbol{a}_{-i}) = P^{\text{non}}_{\text{collision}} \times W \log_2 \{1 + Z_X(a_i)\} + P_{\text{collision}} \\ \times W \log_2 \{1 + \Gamma_X(a_i, \boldsymbol{a}_{-i})\},\ i \in \mathcal{N}, X \in \mathcal{L}. \end{aligned} \tag{5}$$

Let Z_X be the SNR of a user X, $P^{\text{non}}_{\text{collision}}$ be the probability of no packet collisions, and $P_{\text{collision}}$ be the probability of packet collisions. Γ_X is the SINR, which is the ratio of a user X's own signal power to the interference power, and is expressed by the following Eq. (6) [25].

$$\Gamma_X(a_i, \boldsymbol{a}_{-i}) = \frac{P^{\text{receive}}_X(a_i)}{\sum_{X\neq Y, Y\in\mathcal{L}} I_Y(a_i, \boldsymbol{a}_{-i}) + N_0},\ i \in \mathcal{N}, X \in \mathcal{L}, \tag{6}$$

where P^{receive}_X is the received power of an AP when a user X communicates with the AP, I_X is the interference power from users except for user X, and N_0 is the background noise power. In general, an AP can communicate with a user X without packet errors if the signal power from a user X received by an AP is stronger than that of another user [26], [27]. This phenomenon is called the capture effect and can be expressed as the requirement that SINR Γ_X must be larger than a threshold, which can be defined as [26], [27]:

$$\Gamma_X \geq \delta, \tag{7}$$

where δ is a threshold.

P^{receive}_X is obtained by each user's transmit power $P^{\text{send}}_{\text{AP}}$ [11];

$$P^{\text{receive}}_X(a_i) = \frac{g P^{\text{send}}_{\text{AP}}}{\left\{\tilde{d}^{\text{mov}}_X(a_i)\right\}^{\alpha}},\ i \in \mathcal{N}, X \in \mathcal{L}, \tag{8}$$

where g is the antenna gain. In this paper, the users are assumed to move. This is due to the fact that the target of communication is different from that in [11], which assumes an ad hoc network where users communicate with each other. Thus, $\tilde{d}^{\text{mov}}_X$ is the distance between users. However, we assume an AP connection method, and communication is between a user and an AP. Thus, the distance $\tilde{d}^{\text{mov}}_X$ between a moving user after moving and an AP is used. In addition, let α be the path loss exponent. This exponent varies depending on the surrounding environment and is usually $2 < \alpha \leq 4$ [28].

Here, the effective transmission rate R_X of a user X can be approximated by Eq. (9) [11];

$$R_X(a_i, \boldsymbol{a}_{-i}) \approx W \log_2 \{\Gamma_X(a_i, \boldsymbol{a}_{-i})\},\ i \in \mathcal{N}, X \in \mathcal{L}. \tag{9}$$

The interference power I_Y can be expressed in the same way as in Eq. (8).

From Eqs. (5)–(8), we use the moving user's connection position as an optimization parameter and adjust the user's transmit power and SINR to maximize each user's throughput. The combination of strategies that satisfy Eq. (1) using Eq. (2) calculated from (5)–(8), that is, the Nash equilibrium, derives the optimal position of the new user

$\tilde{\boldsymbol{d}}_i^{\text{new}*} = (\tilde{d}_i^{\text{new}*}, \tilde{\psi}_i^{\text{new}*})$. Moreover, our proposed method considers the initial position of users, the transmission rate calculated from their position, and the amount of interference to determine the optimal user position.

Next, we prove that the all user movement game $\mathcal{G}_{\text{all mov}}$ is a potential game $\mathcal{G}_{\text{pot}}$ by using a bilateral symmetric interaction (BSI) game. However, it is difficult to prove directly that the proposed system is a potential game using the utility function u_i in Eq. (2) because the sigma terms are in fractions of this equation, unlike in the equation defined for BSI games [29], [30]. Thus, we redefine the utility function $\hat{u}_i$, which is transformed such that the sigma term in the utility function u_i does not include fractions. We define the utility function $\hat{u}_i$ as:

$$\hat{u}_i(a_i, \boldsymbol{a_{-i}}) = \sum_{n \in \mathcal{N}} \frac{-1}{R_n(a_n, \boldsymbol{a_{-n}})} + \sum_{m \in \mathcal{M}} \frac{-1}{R_m\big(a_j, \boldsymbol{a_{-j}}\big)}. \tag{10}$$

The relationship between u_i and $\hat{u}_i$ can be expressed as Eq. (11),

$$u_i = \frac{-1}{\hat{u}_i}. \tag{11}$$

From Eq. (11), the parameter that depends on u_i is $\hat{u}_i$. Thus, maximizing $\hat{u}_i$ is equivalent to maximizing u_i. As a result, solving all user movement game $\hat{\mathcal{G}}_{\text{all mov}}$ solves all user movement game $\mathcal{G}_{\text{all mov}}$. Therefore, there is no problem if the utility function u_i changes to $\hat{u}_i$.

C. PROOF OF POTENTIAL GAME

In the following, we prove that the all user movement game $\mathcal{G}_{\text{all mov}}$ is a potential game $\mathcal{G}_{\text{pot}}$ defined by the equation [22]. Currently, the BSI game is sufficient as a potential game [22]. In addition, $\mathcal{G}_{\text{all mov}}$ and $\hat{\mathcal{G}}_{\text{all mov}}$ are equivalent. Thus, to prove that it is a potential game, we first prove that the all user movement game $\hat{\mathcal{G}}_{\text{all mov}}$ is a BSI game $\mathcal{G}_{\text{bsi}}$. The definition of a BSI game $\mathcal{G}_{\text{bsi}}$ is as follows,

$$u_i(a_i, \boldsymbol{a_{-i}}) = \sum_{j \in \mathcal{N} \setminus \{i\}} w_{ij}\big(a_i, a_j\big), \forall i \in \mathcal{S}. \tag{12}$$

Each user i, j belongs to player $\mathcal{S}$, and player i's set of strategies is $\mathcal{A}_i$. w_{ij} is a function whose variables are the elements (a_i, a_j), $\mathcal{A}_i \times \mathcal{A}_j$. Moreover, it satisfies $w_{ij}(a_i, a_j) = w_{ji}(a_j, a_i)$ [29], [30].

Theorem 1: The all user movement game $\mathcal{G}_{\text{all mov}}$ is a potential game.

Proof: Replacing u_i in Eq. (12) with $\hat{u}_i$ gives the following:

$$\hat{u}_i(a_i, \boldsymbol{a_{-i}}) = \sum_{j \in \mathcal{N}/\{i\}} w_{ij}\big(a_i, a_j\big), \forall i \in \mathcal{N}. \tag{13}$$

Let N be the number of moving users; then, the proposed system assumes $N = 2$. Hereafter, let the number of moving users N be $N = 2$. Thus, the above equation can be rewritten as Eq. (14).

$$\sum_{j \in \mathcal{N}/\{i\}} w_{ij}\big(a_i, a_j\big) = w_{ij}\big(a_i, a_j\big), j \in \mathcal{N} \setminus \{i\}. \tag{14}$$

To make w_{ij} similar to the utility function $\hat{u}_i$, replace w_{ij} with the following.

$$w_{ij}\big(a_i, a_j\big) = \sum_{k \in \mathcal{N}} \frac{-1}{R_k(a_k, \boldsymbol{a_{-k}})} + \sum_{l \in \mathcal{M}} \frac{-1}{R_l(a_i . \boldsymbol{a_{-i}})}, j \in \mathcal{N} \setminus \{i\} \tag{15}$$

The utility function $\hat{u}_i$ of Eq. (13) is expressed as:

$$\begin{aligned} \hat{u}_i(a_i, \boldsymbol{a_{-i}}) = &\sum_{n \in \mathcal{N}} \frac{-1}{R_n(a_n, \boldsymbol{a_{-n}})} \\ &+ \sum_{m \in \mathcal{M}} \frac{-1}{R_m(a_i, \boldsymbol{a_{-i}})}, j \in \mathcal{N} \setminus \{i\}. \end{aligned} \tag{16}$$

To prove that the all user movement game $\mathcal{G}_{\text{all mov}}$ is BSI game, it is necessary to verify that the function w_{ij} satisfies $w_{ij}(a_i, a_j) = w_{ji}(a_j, a_i)$.

$$\begin{aligned} w_{ij}\big(a_i, a_j\big) = &\sum_{n \in \mathcal{N}} \frac{-1}{R_n(a_n, \boldsymbol{a_{-n}})} \\ &+ \sum_{m \in \mathcal{M}} \frac{-1}{R_m(a_i, \boldsymbol{a_{-i}})}, j \in \mathcal{N} \setminus \{i\}, i \in \mathcal{N} \setminus \{j\}, \end{aligned} \tag{17}$$

$$\begin{aligned} w_{ji}\big(a_j, a_i\big) = &\sum_{n \in \mathcal{N}} \frac{-1}{R_n(a_n, \boldsymbol{a_{-n}})} \\ &+ \sum_{m \in \mathcal{M}} \frac{-1}{R_m\big(a_j, \boldsymbol{a_{-j}}\big)}, j \in \mathcal{N} \setminus \{i\}, i \in \mathcal{N} \setminus \{j\}, \end{aligned} \tag{18}$$

where functions w_{ij} and w_{ji} are Eqs. (17) and (18), respectively, since the second term on the right hand side is different from Eqs. (17), (18). If $R_m(a_i, \boldsymbol{a_{-i}}) = R_m(a_j, \boldsymbol{a_{-j}})$ holds, then the function w_{ij} also holds. It can be verified that $w_{ij}(a_i, a_j) = w_{ji}(a_j, a_i)$ satisfies the conditions of the BSI game. In this system model, i and $j, j \in \mathcal{N} \setminus \{i\}, i \in \mathcal{N} \setminus \{j\}$, correspond to two moving users, and they interact with each other because they interfere with each other [11]. Thus, $R_m(a_i, a_j) = R_m(a_j, a_i), \forall m \in \mathcal{M}$. As a result, from Eqs. (16), (17), (18), we can say that the all user movement game $\hat{\mathcal{G}}_{\text{all mov}}$ is a BSI game $\mathcal{G}_{\text{bsi}}$. Since the BSI game is a sufficient condition for a potential game, the all user movement game $\hat{\mathcal{G}}_{\text{all mov}}$ is a potential game $\mathcal{G}_{\text{pot}}$. As a result, $\mathcal{G}_{\text{all mov}}$ is a potential game $\mathcal{G}_{\text{pot}}$. ■

D. PROPOSED ALGORITHM

There are multiple algorithms for finding Nash equilibrium in potential games [22]. However, spatial adaptive play (SAP) maximizes the potential function with a high probability of the Nash equilibrium converging, and the SAP algorithm has also been shown to have shorter convergence times than other algorithms in previous research [11]. Thus, we use an SAP algorithm in this paper [11]. This method decides a player's next strategy probabilistically.

Algorithm 1 Spatial Adaptive Play (SAP) Algorithm

```
1: Initially, we set $k = 0$.
2: All moving users collect information about the opponent's strategy.
3: The players are randomly selected and denoted by moving user $i, i \in \mathcal{N}$ with the moving user's position $\hat{\boldsymbol{d}}_i^{\mathrm{new}}[k]$.
4: Moving user $i$ calculates the utility value $\hat{u}_i(a_i[k+1], \boldsymbol{a}_{-i}[k])$ for all available strategies on the basis of the received strategies of the opponent.
5: Moving user $i$ updates his/her position strategy according to Eq. (20), and if there is a position that satisfies Eq. (20), the moving user's position $\hat{\boldsymbol{d}}_i^{\mathrm{new}}[k]$ is updated.
6: If the maximum utility is the same, update moving user $i$'s position $\hat{\boldsymbol{d}}_i^{\mathrm{new}}[k]$ to the closer one from the current position.
7: These steps stop if the step count $k$ reaches a certain value; let $\hat{\boldsymbol{d}}_i^{\mathrm{new}}[k]$ be $\tilde{\boldsymbol{d}}_i^{\mathrm{new}*}$, otherwise, return to step 2.
```

Player $i \in \mathcal{N}$ can only change his/her strategy $a_i[k]$ at the kth iteration time. Player i chooses the $k+1$th iteration time strategy $a_i[k+1]$ with probability p_i as follows [22].

$$p_i(a_i[k+1], \boldsymbol{a}_{-i}[k]) = \frac{\exp\left\{\beta \hat{u}_i(a_i[k+1], \boldsymbol{a}_{-i}[k])\right\}}{\sum_{a_i' \in \mathcal{A}_i \setminus \{a_i\}} \exp\left\{\beta \hat{u}_i\left(a_i', \boldsymbol{a}_{-i}[k]\right)\right\}}, \tag{19}$$

where β is a parameter that takes the value $0 < \beta < \infty$; in this calculation, we assume that $\beta = k$ [11]. Using this p_i, player i chooses the strategy that can maximize his/her utility value $\hat{u}_i$.

The maximum utility value can be written using p_i as in [11]:

$$\begin{aligned} &\max \hat{u}_i(a_i[k+1], \boldsymbol{a}_{-i}[k]) \\ &\approx \max\Bigg[p_i(a_i[k+1])\hat{u}_i(a_i[k+1], \boldsymbol{a}_{-i}[k]) \\ &\qquad -\frac{1}{\beta} p_i(a_i[k+1]) \log p_i(a_i[k+1])\Bigg]. \end{aligned} \tag{20}$$

Eq. (20) is used to find the strategy that maximizes the utility value. Details on the SAP algorithm and the all user movement game algorithm are given in Algorithm 1 and Algorithm 2. The Nash equilibrium of our proposed game $\mathcal{G}_{\mathrm{all\,mov}}$ is derived by these algorithms.

IV. NUMERICAL ANALYSIS

The parameter settings for our numerical analysis are shown in Table 2. To simplify the calculations, we assume four users, two of which are moving, as moving fifty out of one hundred users connected to an AP should have the same impact as moving two out of four users.

As mentioned in Section IV, we evaluated the proposed method by comparing the system throughput with that of the previous methods [2], [3]. Moreover, we use the improvement ratio of the system throughput θ as an evaluation basis, which is as follows:

$$\Delta\theta = \frac{\theta_{\mathrm{pro}}}{\theta_{\mathrm{non\,move}}}. \tag{21}$$

Let θ_{pro} be the system throughput of the proposed method and $\theta_{\mathrm{nonmove}}$ be the system throughput when users do not move.

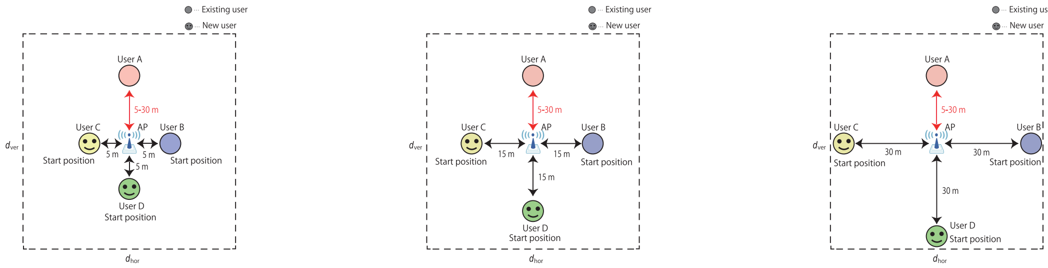
In our numerical analysis, we analyze the characteristics of the users' optimal positions, and the system throughput by varying the position of users, as shown in Fig. 5(a)–(f). Here, each user is denoted as user A, user B, user C,

Algorithm 2 All User Movement Game Algorithm

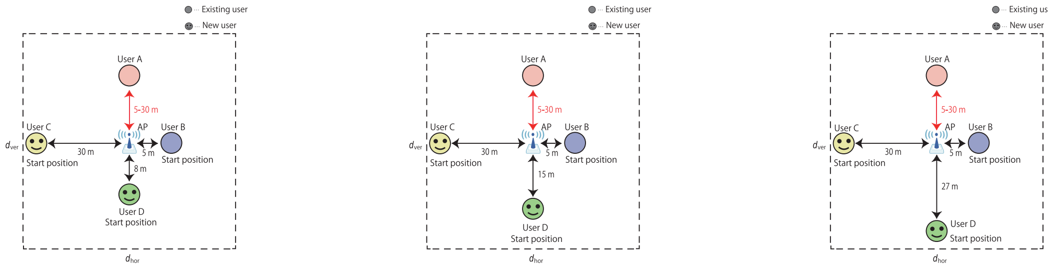
```
Require: $\boldsymbol{d}_X,\ X \in \mathcal{L}, \boldsymbol{d}_Y,\ Y \in \mathcal{L}$
Ensure: $\tilde{\boldsymbol{d}}_i^{\mathrm{mov}*}$
Initially, new users arrive in a limited square region, and we set $\theta = 0$.
for $X = 1 \ldots L$ do
    for $Y = 1 \ldots L$ do
        if $X = Y$ then
            break;
        else if $X \neq Y$ then
            Users $X, Y$ are denoted as moving users $\boldsymbol{c}^{\mathrm{mov}} = (X, Y),\ X \neq Y,\ X, Y \in \mathcal{L}$.
            Moving users $\boldsymbol{c}^{\mathrm{mov}} = (X, Y),\ X \neq Y,\ X, Y \in \mathcal{L}$ run the SAP algorithm [11] based on the position of user $\boldsymbol{d}_X,\ X \in \mathcal{L}, \boldsymbol{d}_Y,\ Y \in \mathcal{L}$. They calculate the system throughput $\theta_{XY}$ and the position $\tilde{\boldsymbol{d}}_i^{\mathrm{mov}} = \operatorname{argmax} \theta_{XY}$.
            if $\theta_{XY} > \theta$ then
                let $\theta$ be $\theta_{XY}$ and let $\tilde{\boldsymbol{d}}_i^{\mathrm{mov}*}$ be $\tilde{\boldsymbol{d}}_i^{\mathrm{mov}}$.
            end if
        end if
    end for
end for
```

TABLE 2. Parameter values.

Parameter	value
Vertical length of area d_{ver}	60 m
Horizontal length of area d_{hor}	60 m
Communication standard	IEEE 802.11g
Number of APs	1
Coordinates of AP $\boldsymbol{d}_{\mathrm{AP}}$	(30, 30) m
Number of moving users N	2
Number of non-moving users M	2
Path loss exponent α	2
Transmit power of terminal P^{send}	32 dBm
Antenna gain g	5.00
SINR thresholds δ	−20 dB
White Gaussian noise N_0	10^{-13} W
Channel bandwidth W	20 MHz
Probability of non-collision $P_{\mathrm{collision}}^{\mathrm{non}}$	3 %
Probability of collision $P_{\mathrm{collision}}$	97 %
Step count k	1000

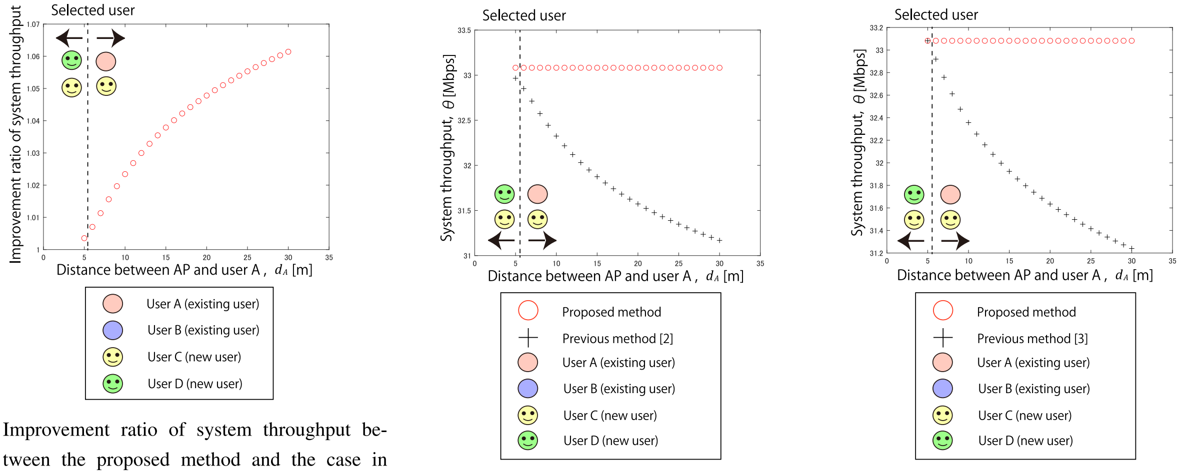


(**a**) Assumed environment of pattern (I). (**b**) Assumed environment of pattern (Ⅱ). (**c**) Assumed environment of pattern (Ⅲ).



(**d**) Assumed environment of pattern (Ⅳ). (**e**) Assumed environment of pattern (Ⅴ). (**f**) Assumed environment of pattern (Ⅵ).

FIGURE 5. Assumed environment.



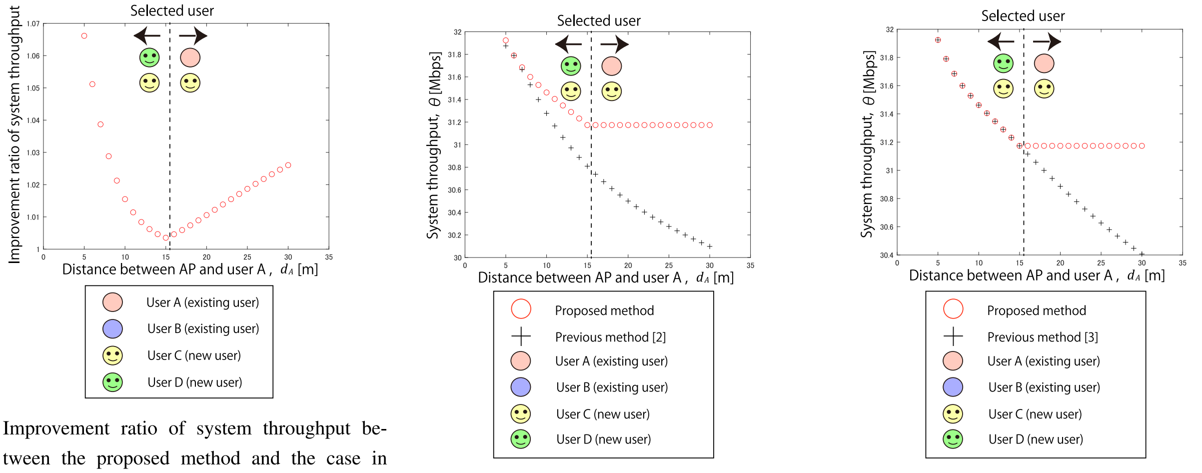
(**a**) Improvement ratio of system throughput between the proposed method and the case in which users do not move. (**b**) System throughput of proposed method and [2]. (**c**) System throughput of proposed method and [3].

FIGURE 6. System throughput of each method in pattern (I).

and user D. In the proposed method, there is no difference between these users. However, there is a clear difference between new users and existing users in the conventional methods [2], [3]. Therefore, we define users A and B as existing users and users C and D as new users in order to compare the conventional methods [2], [3]. As a specific user setup, the initial positions of all users except user A were fixed, and the system throughput was calculated when the initial position of user A $\hat{\boldsymbol{d}}_A$ was changed. We assume six patterns of users' positions. Patterns (I)–(III) are when the distance between the AP and users is equal at the initial position of users, while patterns (IV)–(VI) are when all users cannot be equidistant from the AP.

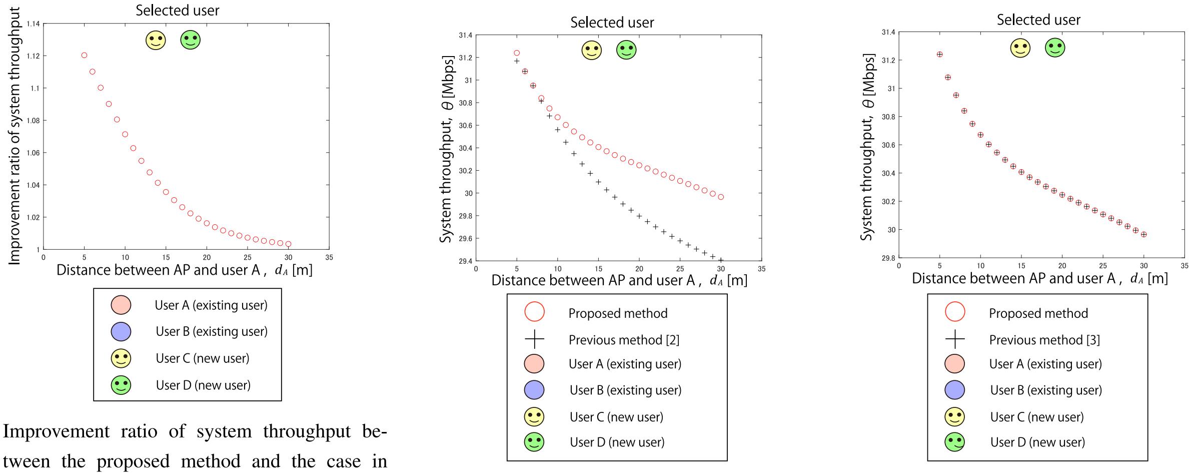
In pattern (I), we set the initial position of user B to $\hat{\boldsymbol{d}}_B = (5, 0°)$, user C to $\hat{\boldsymbol{d}}_C = (5, 180°)$, and user D to $\hat{\boldsymbol{d}}_D = (5, -90°)$, as shown in Fig. 5(a). In pattern (II), we set the initial position of user B to $\hat{\boldsymbol{d}}_B = (15, 0°)$, user C to $\hat{\boldsymbol{d}}_C = (15, 180°)$, and user D to $\hat{\boldsymbol{d}}_D = (15, -90°)$, as shown in Fig. 5(b). In pattern (III), we set the initial position of user B to $\hat{\boldsymbol{d}}_B = (30, 0°)$, user C to $\hat{\boldsymbol{d}}_C = (30, 180°)$, and user D to $\hat{\boldsymbol{d}}_D = (30, -90°)$, as shown in Fig. 5(c).

Fig. 6 shows the system throughput of the proposed method and the other methods in the pattern (I). Specifically, Fig. 6(a) shows the improvement ratio of system throughput $\Delta\theta$ between the proposed method and the case in which users do not move. Fig. 6(b) and Fig. 6(c) compare the system throughput of the proposed method with that of the prior methods [2] and [3], respectively. Similarly, Fig. 7 shows the system throughput of the proposed method and the other methods in the pattern (II), and Fig. 8 shows that



(a) Improvement ratio of system throughput between the proposed method and the case in which users do not move. **(b)** System throughput of proposed method and [2]. **(c)** System throughput of proposed method and [3].

FIGURE 7. System throughput of each method in pattern (II).



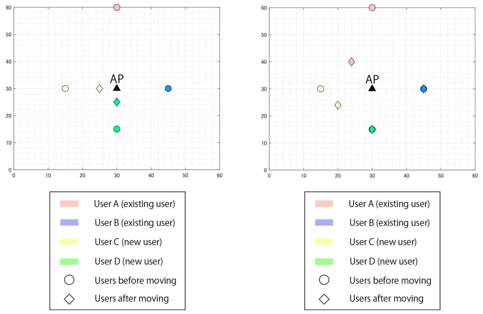
(a) Improvement ratio of system throughput between the proposed method and the case in which users do not move. **(b)** System throughput of proposed method and [2]. **(c)** System throughput of proposed method and [3].

FIGURE 8. System throughput of each method in pattern (III).

in the pattern (III). The horizontal axis represents the initial position of user A.

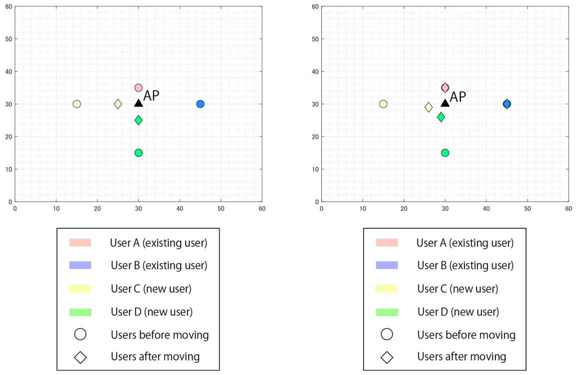
As shown in Figs. 6–8, our proposed method improves system throughput compared to all previous methods [2], [3]. In particular, our proposed method improved system throughput by about 6 % at most compared to [2]. Moreover, the improvement ratio is especially high at the position $d_A = 30$. The cause of this can be explained by Fig. 9, which shows the user's optimal position of each method at $\hat{\boldsymbol{d}}_A = (30, 90^\circ)$ in pattern (II).

In Miyata et al.'s method [2], user C and user D move closer to the AP to obtain a higher transmission rate. However, it does not consider the interference between users and the transmission rates obtained by other users. Therefore, users C and D move closer to the AP, and only user A connects to the AP at a position far from the AP, as shown in Fig. 9(a). Thus, because user A is far from the AP, the transmit power of user A P_A^{receive} received by the AP is low. Moreover, compared to user A, the other connected users are relatively close to the AP. Therefore, the interference Γ_A received by user A also increases. As a result, only the transmission rate of user A will be extremely low, degrading the overall system performance.



(a) Optimal position of each user in previous method [2]. **(b)** Optimal position of each user in proposed method.

FIGURE 9. Optimal position of each user at $\hat{d}_A = (30, 90^\circ)$ in pattern (II).



(a) Optimal position of each user in previous method [2].

(b) Optimal position of each user in proposed method.

FIGURE 10. Optimal position of each user at $d_A = (5, 90°)$ in pattern (II).

Meanwhile, the optimal position of the users in the proposed method cannot be a situation which degrades the overall system performance. This is because users are moved at an equal distance from the AP, considering the interference between users, as shown in Fig. 9(b). Thus, we can assume that the system throughput of the proposed method is significantly higher than that of the previous method, especially in the pattern (I) in which only user A is very far from the AP.

However, for all patterns, the improvement ratio of the system throughput in the proposed method is not higher than that of the previous methods [2], [3] when the initial position of user A is close to the AP. This cause can be explained using Fig. 10. Fig. 10 shows the users' optimal positions for the proposed method and [2] when the initial position of user A in the pattern (II) is $\hat{\boldsymbol{d}}_A = (5, 90^\circ)$.

The closer the user is to the AP, the higher the transmission rate. However, the smaller the distance between the user and the AP, the stronger the effect of interference on other users. Thus, the transmission rate obtained by other users is reduced. The interference has a greater effect on users who are far away from the AP. However, if the initial position of user A in the pattern (II) is $\hat{\boldsymbol{d}}_A = (5, 90^\circ)$, none of the users receives an extremely low transmission rate. Thus, because there are no users who suffer large amounts of interference, the optimal position of the user is close to the AP, even in the proposed method. As a result, the optimal position of users does not differ largely compared to [2] in which users are connected close to the AP. Therefore, the improvement ratio of the system throughput is not good.

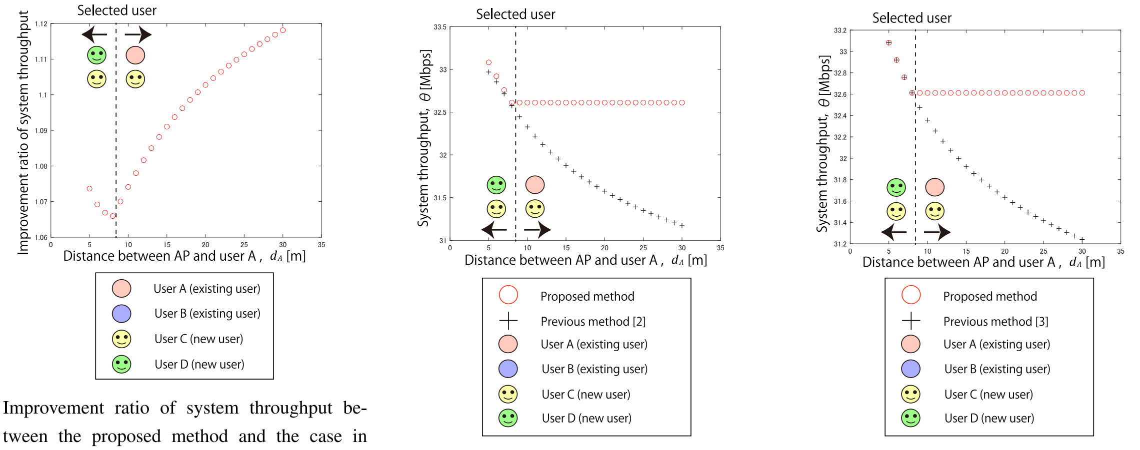
As Fig. 8 shows, there is no difference in value between the system throughput of the proposed method and [3] in the pattern (III), indicating that the user's optimal position are exactly the same in both methods. This is because the transmission rates of users A and B, who were already connected to the AP, are not extremely low. In the pattern (I) and the pattern (II), from a certain initial position of user A, only user A may connect farther away from the AP than the other users. Because user A obtains an extremely low transmission rate, the system throughput will be low unless user A is moved. Therefore, the proposed method, which considers the movement of existing users, is more effective than [3], which only considers new users. However, in the pattern (III), there is no case in which only one user connects at an extremely remote position from the AP even if the initial position of user A $\hat{\boldsymbol{d}}_A$ changes, because the initial positions of users other than user A are already far away from the AP. In other words, there are no existing users (user A and user B) who obtain extremely low transmission rates. As a result, the system throughput of the previous and proposed methods do not differ because only new users (users C and D) move in order to improve the system throughput.

Here, Fig. 6(a), 7(a), 8(a) show the improvement ratio of the system throughput $\Delta\theta$ between the proposed method and the case in which users do not move. From these figures, we can assume that the initial position where all users are at equal distance from the AP has the lowest improvement ratio of the system throughput. However, there are very few situations in which users are connected at equal distance from the AP in a real environment. Therefore, we next analyze the system throughput and users' positions in a situation where all users cannot be at an equal distance from the AP. Specifically, we analyze the patterns in Fig. 5(d)–(f).

Figs. 11, 12, 13 show the system throughput characteristics for pattern (IV), pattern (V), and pattern (VI). From Figs. 11–13, even if the initial positions of each user are unequal, the system throughput improves when the initial position of user A is far away from the AP. In particular, the closer the initial position of user D is to the AP, the higher the system throughput, such as in the pattern (IV). This is similar to the situation in Fig. 9. In the previous methods [2], [3], when the initial position of user A $\hat{\boldsymbol{d}}_A$ is far from the AP, the transmission rate obtained by user A is extremely low, resulting in low system throughput. Therefore, in the pattern (IV), the closer the initial position of user D is to the AP, the higher the interference to user A is. The system throughput in the pattern (IV) is greatly improved because the transmission rate of user A is greatly reduced.

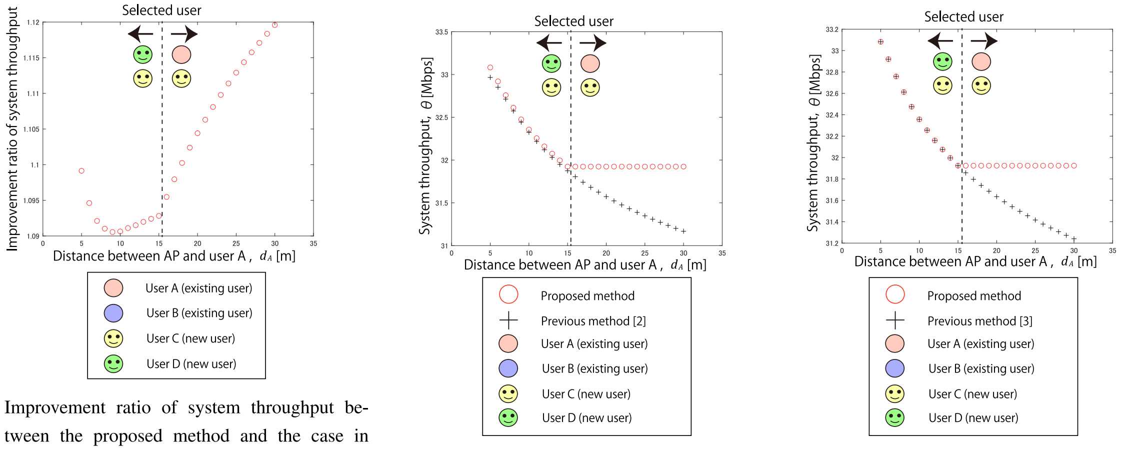
Next, we analyze the characteristics of the users' optimal positions when the users are at unequal distances. As an example, Fig. 14 shows the optimal position of user A in the pattern (IV) when the initial position of user A is $\hat{\boldsymbol{d}}_A = (11, 90^\circ)$ and $\hat{\boldsymbol{d}}_A = (27, 90^\circ)$. In addition, Fig. 15 shows the optimal position of user A in the pattern (VI) when the initial position of user A is $\hat{\boldsymbol{d}}_A = (8, 90^\circ)$ and $\hat{\boldsymbol{d}}_A = (24, 135^\circ)$.

As Fig. 14 shows, if only one of the user's initial positions is far from the AP (i.e., the performance of the entire system degrades due to one user), this user moves closer to the AP. Moreover, even if two users are far away from the AP in their initial positions (which would not degrade the performance of the entire system), these users move closer to the AP. This is because if there are users connected closer to the AP, the transmission power of the users connected closer will be higher. In addition, the transmission rate will be higher. However, the transmission rate of a user who



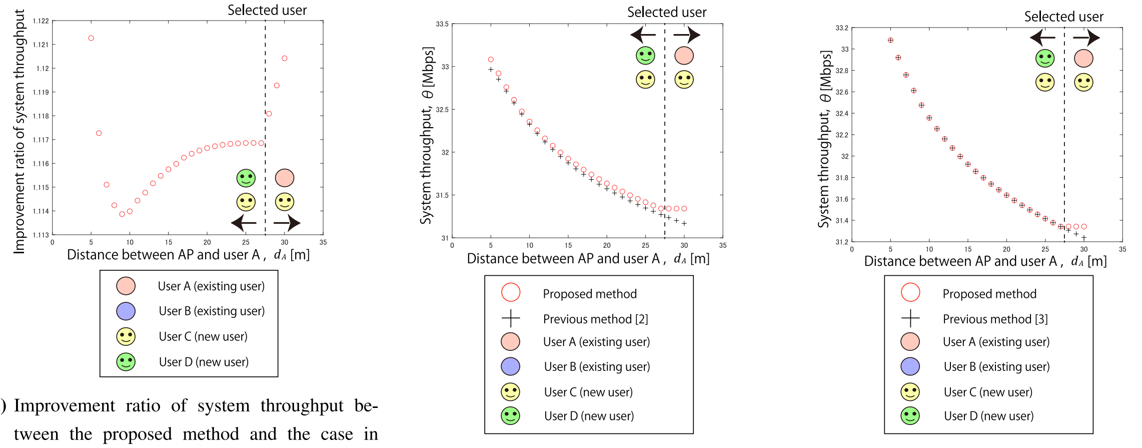
(a) Improvement ratio of system throughput between the proposed method and the case in which users do not move. **(b)** System throughput of proposed method and [2]. **(c)** System throughput of proposed method and [3].

FIGURE 11. System throughput of each method in pattern (IV).



(a) Improvement ratio of system throughput between the proposed method and the case in which users do not move. **(b)** System throughput of proposed method and [2]. **(c)** System throughput of proposed method and [3].

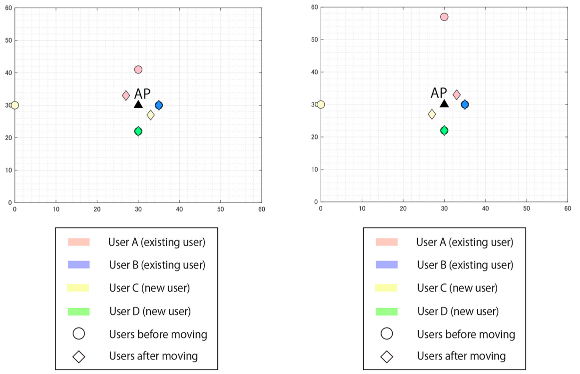
FIGURE 12. System throughput of each method in pattern (V).



(a) Improvement ratio of system throughput between the proposed method and the case in which users do not move. **(b)** System throughput of proposed method and [2]. **(c)** System throughput of proposed method and [3].

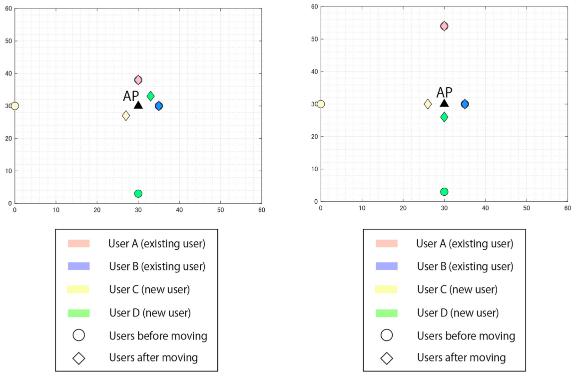
FIGURE 13. System throughput of each method in pattern (VI).

is connected far away from the AP will be much lower because the interference power will be much higher than the user's own transmission power. Therefore, if there are users connected in closer to the AP, there will be users with extremely low transmission rates due to interference, and the system throughput will be degraded. Users who are



(a) Optimal position of each user at $\hat{\boldsymbol{d}}_A = (11, 90^\circ)$. **(b)** Optimal position of each user at $\hat{\boldsymbol{d}}_A = (27, 90^\circ)$.

FIGURE 14. **Optimal position of each user for the proposed method in pattern (IV).**



(a) Optimal position of each user at $\hat{\boldsymbol{d}}_A = (8, 90^\circ)$. **(b)** Optimal position of each user at $\hat{\boldsymbol{d}}_A = (24, 90^\circ)$.

FIGURE 15. **Optimal position of each user for the proposed method in pattern (VI).**

far away from the AP need to increase their own transmit power and reduce interference. As a result, the user who is initially far away from the AP moves closer to the AP. For the same reason, users who are connected at far away from the AP move closer to the AP in Fig. 15(a). As shown in Fig. 15(b), even when only one of the users' initial positions is connected closer to the AP, users who are connected far away from the AP will move closer to the AP. In this case, only user A is connected far away from the AP, which causes the transmission rate of user A to be extremely low. However, even if one user obtains an extremely low transmission rate, three users make up for the negative factor because the three users connect closer to the AP, thus increasing throughput.

There are exceptions in which it is more effective to place all users at an equal distance, as in pattern (II) and pattern (III). This is because two users alone cannot make up for the lower transmission rate, even if the two users who are far away move closer to the AP. As a result, we can assume that the optimal position would be to place all users at an equal distance.

From the above discussion, our conclusion is two factors:

- A user who is far away from the AP should move closer to the AP.
- If there are no users connected close to the AP, the position of all users should be equally far away because two users alone cannot make up for the lower transmission rate.

V. CONCLUSION

We have proposed an AP connection method to maximize system throughput considering interference frequency and the initial positions of all users. The proposed method successfully maximizes system throughput considering the interference frequency and the performance degradation of the overall system when one user obtains an extremely low transmission rate. By proving that this problem is based on a potential game, we were able to theoretically analyze the complex wireless network environment. In the future, we aim to consider user incentives and analyze a situation in which the number of users increases.

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