Game-theoretic Analysis for Multibandwidth WLAN Channel Selection by Coordinated APs

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***Abstract*—As the demand for high-throughput communications in wireless LANs increases, the need for expanding channel bandwidth also increases. However, the use of wider band channels results in the decrease of the number of channels available. Therefore, if multiple access points (APs) are in proximity and the cells overlap, it is difficult for each AP to use an orthogonal channel, and competitions thus increase between the APs using the same channel. To cope with this problem, this paper proposes coordinating APs to increase throughputs at Nash equilibria. A centralized controller coordinates the APs, which jointly select multibandwidth channels. To clarify the effect of coordinating APs, we assume a simple scenario where the cells of three APs overlap, and each AP can select multibandwidth channels. In this scenario, we consider two packet length assumptions. In the first case, the data bit amount of each packet is assumed to be the same. Thus, the packet length changes depending on a data rate. The other case assumes that the packet length is the same regardless of the data rate. Through game-theoretic analysis, it can be clarified that the coordinated APs are able to select channels more effectively than if each AP independently selects channels and that the total throughput of the coordinated APs at Nash equilibria is improved by at most 80 % in two packet length assumptions.**

I. INTRODUCTION

Wireless LANs have become more popular, and wireless LAN cells often overlap. Such cells are called overlapping base service sets (OBSS). When the cells of multiple access points (APs) overlap and the APs select the same channel, inter-cell interference (ICI) occurs. ICI causes a decrease in throughput; therefore, in such a scenario, channel selection is important.

In IEEE 802.11ac [1], [2], 80 MHz and 160 MHz channels will be added, implying that 20 MHz, 40 MHz, 80 MHz, and 160 MHz channels will be available. However, expanding the channel bandwidth causes a decrease in the number of channels, rendering it difficult for each AP to select an orthogonal channel, which consequently results in an increase in ICI.

To solve the problems in channel selection, some methods for selecting channels have been proposed. One method [3] involves using information on the distance between APs and the channels that each AP uses and deciding which channel to select. Another method [4] involves dynamically changing a channel to minimize interference generated by neighboring APs.

In this paper, we propose a framework for increasing throughput at Nash equilibria. In this method, a centralized controller coordinates multiple APs, and these APs jointly select multibandwidth channels. As a result, APs can select channels more effectively when they are coordinated. We aime to achieve higher total throughput of the coordinated APs. As an initial study, we assume the following simple scenario: there are three APs, and the cells of all the APs completely overlap. To evaluate the effect of coordinating APs, two APs are coordinated and they jointly select channels. We compare a case in which each AP operates independently and a case in which two APs are coordinated. Through this comparison and game-theoretic analysis, we clarify that the total throughput of the coordinated APs at Nash equilibria increase.

In this scenario, we consider two packet length assumptions. In the adaptive packet length (APL) case, the data bit amount of each packet is assumed to be the same. Thus, the packet length changes depending on a data rate. Here, the packet length is the duration time to transmit one packet. In the fixed packet length (FPL) case, the packet length is the same regardless of the data rate. Therefore, the transmission time per packet differs between the different data rate. By comparing these two cases, we show that the channel arrangements at Nash equilibria are the same in two cases and verify the appropriateness about the packet length change.

This paper is organized as follows. Section II presents an overview on IEEE 802.11ac and game theory. Section III describes game-theoretic analysis. Section IV presents our conclusion.

II. BACKGROUND

A. IEEE 802.11ac

To increase throughput, in IEEE 802.11ac, 80 MHz and 160 MHz bandwidth channels will be added to the available channel bandwidth, and the maximum number of spatial streams will total 8. By using these maximum values, we will be able to achieve a data rate per channel of over 1 Gbit/s.

In IEEE 802.11ac, an AP selects one 20 MHz channel as a primary channel. When the AP selects a 40 MHz channel, the AP has to select a channel from the channels shown in Fig. 1. For example, if the AP selects the third 20 MHz channel in

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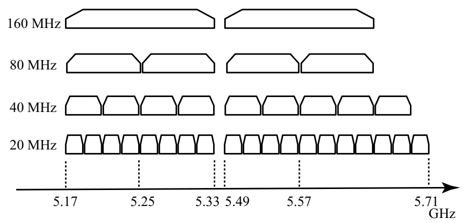

Fig. 1. Available frequency band in Japan.

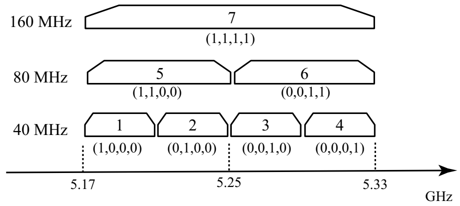

Fig. 2. Available frequency bands.

Fig. 1 as the primary channel, the AP should select the fourth 20 MHz channel as the secondary channel, the first and second 20 MHz channels as a secondary40 channel, and the fifth, sixth, seventh, and eighth 20 MHz channels as secondary80 channels.

Here, we assume a scenario wherein an AP selects a 160 MHz channel. The primary, secondary, and secondary80 channels are idle, and the secondary40 channel is busy. The AP uses continuous channels, so in this case, the AP can use a 40 MHz bandwidth channel. On the other hand, if only the secondary80 channel is busy, the AP can use a 80 MHz bandwidth channel. In this manner, when each AP transmits frames, they are able to use only idle channels, and these channels should be continuous.

B. Game Theory [5], [6]

Game theory is used for the mathematical analysis of strategic interaction. A game is a formal representation of a scenario in which a number of individuals interact with each other in a setting of strategic interdependence. This mean that each individuals welfare depends not only on her own actions but also on the actions of the other individuals.

In the following, we explain the definition of strategic-form games. In addition, the concept of best-response correspondence and Nash equilibrium are presented.

1) Strategic-Form Games: A game in a strategic form has three elements: The set of players $\mathcal{N} = \{1,\ 2,\ \ldots,\ N\}$, the pure-strategy space $\mathcal{A}_i$ for each player i, and the payoff function u_i for each player i. The pure strategy excluding players i is denoted by $\boldsymbol{a}_{-i} = (a_1, \ldots, a_{i-1}, a_{i+1}, \ldots, a_N)$. $\mathcal{A}$ is the set of the pure-strategy space of all players, i.e., $\mathcal{A} = \{\mathcal{A}_1 \times \cdots \times \mathcal{A}_i \times \cdots \times \mathcal{A}_N\ \}$. For a game with N players, the normal-form representation specifies for each player i, the pure-strategy space $\mathcal{A}_i$ and a utility u_i associated with the outcome arising from $a_1, \ldots, a_N$. Formally, we write $(\mathcal{N}, \mathcal{A}, \{u_i\}_{i\in\mathcal{N}})$.

2) Best-Response Correspondence: We can say that player i's best-response correspondence b_i: $\mathcal{A}_{-i} \to \mathcal{A}_i$ in the game $(\mathcal{N}, \mathcal{A}, \{u_i\}_{i\in\mathcal{N}})$, is the correspondence that assigns to each $a_{-i} \in \mathcal{A}_{-i}$ the set

$$b_i(\boldsymbol{a}_{-i}) = \{a_i^\star \in \mathcal{A}_i : u_i(a_i^\star, \boldsymbol{a}_{-i}) \geq u_i(a_i, \boldsymbol{a}_{-i}) \forall a_i \in \mathcal{A}_i\}. \tag{1}$$

3) Nash Equilibrium: With the notion of the best-response correspondence, we can define the Nash equilibrium as follows: The strategy profile $(a_1^\star, \ldots, a_N^\star)$ is the Nash equilibrium of game $(\mathcal{N}, \mathcal{A}, \{u_i\}_{i\in\mathcal{N}})$ if and only if $a_i^\star \in b_i(\boldsymbol{a}_{-i}^\star) \forall i$.

III. Game-theoretic Analysis for Multibandwidth Channel Selection by Coordinated APs

A. System Model

In this paper, as an initial study, we assume the following simple scenario; there are three APs, where the cells of all the APs completely overlap. For simplicity, we assume that all APs and stations are able to sense the frames transmitted from all the other APs and stations, and the interferences between channels at different frequencies are negligible. We also assume the individual and coordination modes. In the individual mode, each of three APs independently selects channels, with the aim of maximizing its own throughput. In the coordination mode, a centralized controller coordinates APs 1 and 2, which jointly select channels to maximize their total throughput, whereas AP 3 selects a channel to maximize its own throughput.

In the following, we explain the details of the assumed scenario, formulation process.

1) Available Frequency Bands and Channels: Each AP selects a channel from the following three types of bandwidth channels: 40 MHz, 80 MHz, and 160 MHz. Here, we exclude the 20 MHz channel without loss of generality, because it is sufficient for us to consider three orthogonal channels for three APs and there are four 40 MHz orthogonal channels.

For simplicity, we assume that available frequency bands range are from 5.17 GHz to 5.33 GHz, and we number the channels from 1 to 7 as seen in Fig. 2, where "0" represents an idle channel and "1" represents a busy channel. For example, (0,0,1,1) represents channel 6.

2) Game-theoretic Formulation: The throughput maximization discussed in Sec. III-A2a can be treated as a game where players are APs, strategies are channels, and utility is throughput. Thus the pure-strategy space of player i is $\mathcal{A}_i = \{(0,0,0,1), (0,0,1,0), (0,1,0,0), (1,0,0,0), (0,0,1,1), (1,1,0,0), (1,1,1,1)\}$. Cell i is defined as the communication range of AP i.

a) Channel Arrangement: Here, we consider cases in which the channels selected by each AP overlaps. First, we consider a case in which the channels selected by three APs totally or partially overlaps. We assume that the primary channels of all APs are the same.

Next, we consider a case in which the channels selected by two APs totally or partially overlap . In this case, we assume that the primary channels selected by two APs are the same.

Finally, we consider a case in which there are two orthogonal channels selected by APs j and k in the channel bandwidh selected by AP i. Here, AP i should select its primary channel in accordance with the primary channel of AP j or AP k. In this paper, we assume a scenario where APs 1 and 2 are coordinated. Therefore, if the channels of APs 1 and 2 overlap, we assume that the primary channels of APs 1 and 2 are the same.

As an example, we consider a case: $a_1 = (1,1,1,1), a_2 = (1,1,0,0), a_3 = (0,0,1,1)$. AP 1 selects a $160\,\mathrm{MHz}$ channel, whereas APs 2 and 3 select different $80\,\mathrm{MHz}$ channels overlapping with the $160\,\mathrm{MHz}$ channel selected by AP 1. Here, the primary channels of APs 1and 2 are the same. On the other hand, the primary channel of AP 3 differs from that of APs 1 and 2. When AP 1 attempts to transmit a frame, AP 1 senses the carriers of primary, secondary, secondary40, and secondary80 channels in turn. At this time, all channels are only just idle, because the primary, secondary, and secondary40 channels of AP 1 are frequently used by AP 2, and the secondary80 channels of AP 1 is frequently used by AP 3. Therefore, even if the primary, secondary, and secondary40 channels are idle, the secondary80 channel is often busy. Thus, we equivalently treat the channel arrangement of AP 1 is $a_1 = (1,1,0,0)$ In the same manner, when there are two orthogonal channels selected by APs j and k in the channel bandwidth selected by AP i, the channel arrangement of AP i is equivalently treated as in this example.

After considering this equivalent channel arrangement, the total throughput of each cells is calculated. These throughputs represent the minimum throughput that each cells achieves. The channel assignment of AP i is denoted by a_i, The channel assignment applied in this assumption is denoted by a'_i. In this example, the channel assignment of AP 1 is $a_1 = (1,1,1,1)$, and the equivalent channel arrangement is $a'_1 = (1,1,0,0)$.

b) Data Rate: Here, we define the data rate. Stations accommodated by an AP are assumed to be in proximity. In this case, when the AP selects a $40\,\mathrm{MHz}$ channel, we assume that all the stations achieve a SNR that facilitates a data rate of $270\,\mathrm{Mbit/s}$. We consider the case in which this AP selects a $80\,\mathrm{MHz}$ channel. As described in [7], the receiver sensitivity when an AP selects a $80\,\mathrm{MHz}$ channel is $3\,\mathrm{dB}$ higher than that when an AP selects a $40\,\mathrm{MHz}$ channel. Therefore, when the channel bandwidth doubles, we select a modulation and coding scheme (MCS) for decreasing the receiver sensitivity by $3\,\mathrm{dB}$. By taking this into account, when an AP selects an $80\,\mathrm{MHz}$ channel, the data rate of the AP is $468\,\mathrm{Mbit/s}$, and when an AP selects a $160\,\mathrm{MHz}$ channel, its data rate is $702\,\mathrm{Mbit/s}$.

The MCS, number of streams, and packet length are listed in Table I. The guard interval is $800\,\mathrm{ns}$ and the number of streams is two at the all data rates. Here, we consider two cases of packet length in each data rate.

In APL case, when the channel bandwidth is changed, the packet length also changes depending on a data rate as shown in Table I. For ease of analysis, the transmission time of each packet is set so that the times are identical regardless of their data rate. If two packets transmitted at other data rates collide, the collision time is the same. Therefore, the saturated throughput is the same at any data rate. The relationship between the saturated throughput and the number of transmitting stations is shown in Fig. 3, where l_i is the number of transmitting stations, and $\rho(l_i)$ is the normalized saturated throughput.

TABLE I
PARAMETERS.

Channel bandwidth	Modulation	Coding rate	Packet size (APL case)
$40\,\mathrm{MHz}$	64QAM	$5/6$	$25000\,\mathrm{B}$
$80\,\mathrm{MHz}$	64QAM	$2/3$	$43300\,\mathrm{B}$
$160\,\mathrm{MHz}$	16QAM	$3/4$	$65000\,\mathrm{B}$

On the other hand, in FPL case, the packet length is always $65000\,\mathrm{B}$ regardless of channel bandwidth. In this case, if two packets transmitted at different data rate collide, the collision time depends on the data rate of each packet transmitted. Therefore, we should calculate the throughput of all patterns according to the data rates of each packet transmitted.

c) Impact of Number of Stations on Throughput: Here, we explain how to calculate throughput. The carrier sense multiple access with collision avoidance (CSMA/CA) protocol depends on the random transmission of the frames in CSMA/CA networks. However, the total throughput decreases [8] as the number of stations increases. This is because the backoff window is doubled at each retransmission if the collisions of frames occur, and a station must wait a random backoff time. Here, RTS/CTS is not considered.

When each AP selects orthogonal channels, they do not suffer from interference. However, when some APs select the same channels, or a part of selected channels overlaps, they suffer from interference.

Each AP has five stations. Let the number of stations and the APs in cell i be denoted by m_i. Here, each AP is assumed to have five stations, i.e., $m_i = 6$. Let the number of stations and APs that use the same channel of AP i be denoted by $l_i(a'_i, \boldsymbol{a}'_{-i})$. Here, $\sum_{j\in\mathcal{N}\setminus\{i\}} a'_i a'^{\mathrm{T}}_j = 0$ represents the scenario where each AP selects orthogonal channels, where T reprerents transposition. On the other hand, $\sum_{j\in\mathcal{N}\setminus\{i\}} a'_i a'^{\mathrm{T}}_j \neq 0$ represents the scenario where the channels of AP i and AP j overlap. By using these expressions, $l_i(a'_i, \boldsymbol{a}'_{-i}) = \sum_{j\in\mathcal{N}\setminus\{i\}} m_j H_0(a'_i a'^{\mathrm{T}}_j)$. Here, $H_0(t)$ denotes the Heaviside step function; $H_0(t) = 1\ (t > 0), H_0(t) = 0\ (t \le 0)$.

d) Adaptive packet length Case: Let the bandwidth when AP i chooses strategy a'_i be denoted by $B_{a'_i} \in \{270\,\mathrm{Mbit/s}, 468\,\mathrm{Mbit/s}, 702\,\mathrm{Mbit/s}\}$, and the transmission time per packet be denoted by T_i. From [8], $\rho(l_i)$ is shown in Fig. 3.

By using these expressions, the throughput when cells i, j,

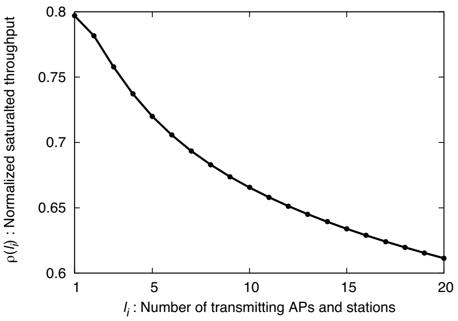

Fig. 3. Saturated throughput versus number of stations (APL case).

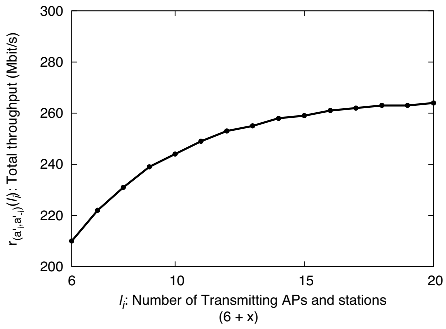

Fig. 4. Saturated throughput versus number of stations (FPL case). 40 MHz: 6 stations. 80 MHz: x stations.

and k overlap is calculated as

$$u_i(a_i, \boldsymbol{a}_{-i}) = B_{a'_i} \times \rho(l_i(a'_i, \boldsymbol{a}'_{-i})) \times \frac{m_i T_i}{m_i T_i + m_j T_j + m_k T_k}. \quad (2)$$

In [9], the throughput of each AP is calculated by the number of stations selecting the same channel. Moreover, because the transmission time per packet is assumed to be the same in any data rate. i.e., $T_i = T_j = T_k$, (2) can be written as

$$u_i(a_i, \boldsymbol{a}_{-i}) = B_{a'_i} \times \rho(l_i(a'_i, \boldsymbol{a}'_{-i})) \times \frac{m_i}{l_i(a'_i, \boldsymbol{a}'_{-i})}. \quad (3)$$

To illustrate this throughput calculation, let us calculate the throughput of the case: $a_1 = (1,1,1,1), a_2 = (1,1,0,0), a_3 = (0,0,1,1)$. First, from Sec. III-A2a, the channel arrangement of each AP is equivalently treated as follows: $a'_1 = (1,1,0,0), a'_2 = (1,1,0,0), a'_3 = (0,0,1,1)$ From (3), $u_1(a_1, \boldsymbol{a}_{-1})$ is

$$u_1(a_1, \boldsymbol{a}_{-1}) = 468\,\mathrm{Mbit/s} \times 0.65 \times \frac{6}{12} = 152\,\mathrm{Mbit/s}. \quad (4)$$

In the same manner, $u_2 = 152\,\mathrm{Mbit/s}$, $u_3 = 330\,\mathrm{Mbit/s}$.

e) Fixed packet length Case: In this case, if two packets transmitted at different data rate collide, the collision time depends on the data rate of each packet transmitted. Because the throughput also depends on the collision time, we are not able to divide the factor about throughput into $B_{a'_i}$ and $\rho(l_i(a'_i, \boldsymbol{a}'_{-i}))$. Therefore, we should calculate the throughput of all overlapping channel patterns according to the data rates of each APs and stations.

Let the saturated throughput be denoted by $r_{(a'_i,\boldsymbol{a}'_{-i})}(l_i(a'_i, \boldsymbol{a}'_{-i}))$. From [8], we calculate $r_{(a'_i,\boldsymbol{a}'_{-i})}(l_i(a'_i, \boldsymbol{a}'_{-i}))$ at all the overlapping channel patterns, and calculate the throughput of each AP. By using $r_{(a'_i,\boldsymbol{a}'_{-i})}(l_i(a'_i, \boldsymbol{a}'_{-i}))$,

$$u_i(a_i, \boldsymbol{a}_{-i}) = r_{(a'_i,\boldsymbol{a}'_{-i})}(l_i(a'_i, \boldsymbol{a}'_{-i})) \times \frac{m_i}{l_i(a'_i, \boldsymbol{a}'_{-i})}. \quad (5)$$

To illustrate this throughput calculation, let us calculate the throughput of the case: $a_1 = (1,1,0,0), a_2 = (0,0,1,1), a_3 = (0,0,1,0)$. $r_{(a'_i,\boldsymbol{a}'_{-i})}(l_i(a'_i, \boldsymbol{a}'_{-i}))$ of APs 2 and 3 is shown in Fig. 4. From (5) and Fig. 4,

$$u_2(a_2, \boldsymbol{a}_{-2}) = u_3(a_3, \boldsymbol{a}_{-3}) = 250\,\mathrm{Mbit/s} \times \frac{6}{12} = 125\,\mathrm{Mbit/s}. \quad (6)$$

In the same manner, we calculated the throughput of all the other overlapping channel patterns.

3) Game-theoretic Formulation:

a) Formulation of Individual Mode: APs 1, 2, and 3 are players 1, 2, and 3. The throughput of AP i is $u_i(a_i, a_{-i})$ when AP i selects a_i. Therefore, this case is formulated as $(\mathcal{N} = \{1,2,3\}, \mathcal{A}_1 \times \mathcal{A}_2 \times \mathcal{A}_3, \{u_1, u_2, u_3\})$.

b) Formulation of Coordination Mode: In this case, a centralized controller is player 12, and AP 3 is player 3. Player 12 coordinates APs 1 and 2, and thus the pure-strategy space $\mathcal{A}_{12}$ is $\mathcal{A}_1 \times \mathcal{A}_2$, which means that the pure-strategy space is expanded by compared with that of the individual mode. The utility of the player 12 is the total throughput of APs 1 and 2, so $u_{12}(a_{12}, a_{-12})$ is $u_{12}(a_{12}, a_{-12}) = (u_1(a_1, a_{-1}) + u_2(a_2, a_{-2}))$. Therefore, this scenario is formulated as $(\mathcal{N}' = \{12, 3\}, \mathcal{A}_{12} \times \mathcal{A}_3, \{u_{12}, u_3\})$.

B. Discussion

1) Comparison of APL Case and FPL Case: The throughputs at each channel arrangement differ between APL case and FPL case in Figs. 5 and 6. However, the channel arrangements at Nash equilibria are the same. Thus, the effect of the change of packet length is smaller than that of the channel arrangement. Therefore, the channel arrangement is important for each AP to get high throughput.

2) Individual Mode: In this mode, there are 14 Nash equilibria represented by $\times$ in Figs. 5 and 6. At these Nash equilibria, the available frequency bands shown in Fig. 2 are completely used by three APs, and the channel arrangements are broadly divided into three patterns. In the first pattern, all APs select the same 160 MHz channel. In the next pattern, each APs selects an orthogonal channel. In the final pattern, all APs largely select a 80 MHz channel, and the channels of two APs overlap. Here, we discuss these three patterns one by one.

First, we focus on Nash equilibrium N. At point N, the strategies of all APs are $a_1^\star = a_2^\star = a_3^\star = (1,1,1,1)$, i.e., all

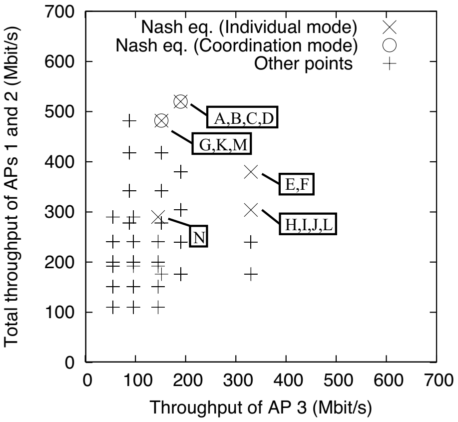

Fig. 5. Throughput of Individual Mode and Coordination Mode (APL Case).

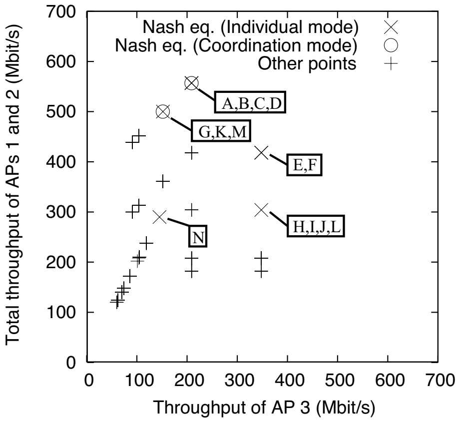

Fig. 6. Throughput of Individual Mode and Coordination Mode (FPL Case).

APs select the same 160 MHz channel, which causes severe competition among APs and stations, and degrades throughput.

Next, we focus on Nash equilibrium point A. At point A, each AP selects an orthogonal channel, and thus, no competition occurs among the APs. The scenarios for points B, C, D, E, and F are considered in the same manner.

Finally, we focus on Nash equilibria G, H, I, J, L, M, and K. At these Nash equilibria, all APs largely use an 80 MHz channel, and the channels of two APs overlap.

3) Coordination Mode: In this mode, there are seven Nash equilibria represented by ○ in Figs. 5 and 6. Points E, F, H, I, J, L, and N are excluded from Nash equilibria.

At points E and F, the total throughput of APs 1 and 2 is lower than the throughput of Nash equilibria A, B, C, and D. This is because the total channel bandwidth of APs 1 and 2 at points E and F is narrower than that at points A, B, C, and D. Therefore, points E and F are excluded from Nash equilibria.

At points H, I, J, and L, APs 1 and 2 select the same 80 MHz channel. Thus, the total throughput of APs 1 and 2 is lower than the throughput of Nash equilibria H, I, J, and L, and points H, I, J, and L are therefore excluded from Nash equilibria.

4) Comparison of Individual Mode and Coordination Mode: In the individual mode, three APs independently select channels, where each AP selects a channel to maximize its own throughput. As a result, points at which the total throughput of APs 1 and 2 is lower also become Nash equilibria.

On the other hand, in the coordination mode, APs 1 and 2 are coordinated, where APs 1 and 2 jointly select their channels to maximize total throughput of APs 1 and 2, and AP 3 selects a channel to maximize its own throughput. Therefore, APs 1 and 2 only chose the strategies that increase the total throughput of APs 1 and 2, and only those points at which the total throughput of APs 1 and 2 is higher become Nash equilibria.

IV. Conclusion

In this paper, we focused on the effect in AP coordination systems. To evaluate this effect, we assumed a scenario in which there are three APs and the cells of each AP overlap. We considered the following two modes. In the first mode, three APs independently select channels, where each AP selects a channel to maximize their own throughput. The second mode is that APs 1 and 2 are coordinated, whereby they jointly select their channels to maximize their total throughput and AP 3 selects a channel to maximize its own throughput. Furthermore, we considered two packet length assumptions. In the first case, the packet length changes depending on a data rate. The other case assumes that the packet length is the same regardless of the data rate. We formulated these cases as games. By comparing these two modes in two packet length assumptions, we established that the coordination of APs increases the expected total throughput of APs 1 and 2 at Nash equilibria in two packet length assumptions.

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