Decentralized Access Point Selection Architecture for Wireles LANs

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Abstract

Wireless LANs have been widely deployed, and multiple access points (APs) will be much more likely to be available there for STAs, which can roam from one AP to another by some rule. We here focus on an efficient and fair way to use the wireless access resources provided by multiple APs. In particular, our major concern is to develop a decentralized way to enable each of STAs to select an appropriate one of available APs independently. A straightforward way is to select an AP with strongest signal, which will be, however, shown to need further improvement. Hence, we propose decentralized AP selection strategies to achieve an efficient and fair share of wireless access resources, and evaluate them by simulations. Through our results, the proposed strategies can attain an excellent throughput performance by use of the number of active STAs sharing each AP even if STAs employ the strategies only when entering the wireless LAN. In addition, if STAs roam from one AP to another in response to changing situation, the total throughput and fairness can be further improved very much.

keyword

Wireless LAN, Wireless Station(STA), Access Point(AP), Roaming, Fairness, Autonomous

1. Introduction

Widespread deployment of IEEE 802.11 wireless LAN [1], [2] is currently progressing. The family of IEEE 802.11 wireless LANs [3], [4] are pervading diverse places such as hotels and airports as well as offices and home in recent years because they can provide a great deal of flexibility and high bandwidth. In consequence, they actually provide convenient and important ways to access the Internet.

With the spread of wireless LAN, multiple APs will be much more likely to be available there fore STAs. Since STAs share the communication resource provided by APs, multiple APs are required to serve many STAs and to improve the transmission capacity in the wireless LAN. In fact, IEEE 802.11 wireless LAN can extend the communication range through the multiple APs. Consequently, the following significant issue can arise in those cases: how to select an appropriate AP among available APs. In the existing architecture, the received signal strength is usually used to select an AP. However, such AP selection strategy causes the concentration of STAs to specific APs: many STAs may associate with only a few APs because their signal strengths measured by the STAs are strong; while only a few STAs may associate with the remaining APs. This results in imbalanced traffic load on APs in the wireless LAN, thereby degrading the fairness in STA throughput and harming an efficient use of the wireless LAN resource. Indeed, many studies have shown the traffic characteristics and user behavior in the wireless LAN [5], [6], [7], [8], and they report that traffic load is often distributed quite unevenly among APs.

There are two possible ways in order to solve this problem; centralized approach and decentralized approach. In the former, centralized approach, an intelligent management system connected with wireless LAN controls the association between APs and STAs. [9] proposes and evaluates such centralized architecture. Various vendors of wireless LAN also implement load-balancing feature in their enhanced network products. However, such intelligent feature is placed as enhanced function and provided in conjunction with the authorization and security management server installed in the wireless LAN, so that additional cost is needed to install it in an existing wireless LAN. In addition, since these products do not take into account compatibility with other vendors, there is problem in the interoperability.

On the other hand, in the latter one, instead of AP and management server, each STA selects the AP based upon some algorithms. As a simple case, in existing wireless LANs, the STA selects the AP with maximum received signal strength. However, it causes imbalanced traffic load in the wireless LAN, as mentioned above. Accordingly, our concern will be as follows in this context; what kinds of information will help STAs to select the best AP? How should STAs select APs based upon the available information?

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Therefore, in this paper, we study the above issues for achieving an efficient and fair share of wireless access resources. The proposed decentralized architecture is simple and scalable compared with the centralized architecture; it only needs slight modification for the STAs and APs, and there is no need of the additional cost because it does not require centralized server. We here consider both dynamic selection scheme and one-time selection one. The former allows each STA to dynamically change its accessing AP in response to changing condition of wireless link etc., and in the latter each STA selects its AP only once when entering the wireless LAN domain and does not change it until leaving there. In these cases, the proposed architecture will be evaluated through simulation and compared with existing architecture, and be shown that the proposed architecture can attain the excellent throughput performance and improve total throughput and fairness in STA throughput very much.

2. IEEE 802.11

In this section, we present the overview of the IEEE 802.11 architecture. At first, we describe network conformation of wireless LAN. In addition, we illustrate AP initial association procedure and clarify issues arising from AP selection.

2.1. Network Types

The fundamental building block of the IEEE 802.11 wireless LAN is basic service set (BSS), which is a set of STAs. The BSS consists of two types networks: the ad hoc network and the infrastructure network. We are considering the autonomous AP (Access Point) selection strategy in the infrastructure network in this paper.

Since the spatial coverage of a single BSS and transmission capacity of a single AP are limited, the AP supports range extension by providing the integration points for network connectivity between multiple BSSs, which forming an extended service set (ESS), as shown in Fig. 1. STAs within the same ESS may move from one BSS to another transparently. The ESS consists of multiple BSSs that are integrated together using a common distribution system (DS). In wireless LANs with the ESS, STAs must thus select an appropriate AP among available APs in a way to achieve an efficient use of wireless resources provided.

2.2. Scanning and AP selection

In an infrastructure network, STAs must associate with an AP within a specific BSS. Accordingly, STA must first find the AP to communicate with others in an infrastructure network, and the process of finding APs is called scanning.

Scanning may be either passive or active. Passive scanning involves only listening to IEEE 802.11 traffic. In the passive scanning procedure, the STA sweeps from channel to channel and records information from all Beacons it receives. At the conclusion of the passive scan, which may involve listening to one or more channels, the STA has accumulated information about the BSSs in its vicinity. Active scanning requires the scanning STA to transmit and elicit responses from APs. In an active scan, the STA will move to a channel and transmit a Probe Request frame. If there is a BSS on the channel that matches the Service Set Identifier (SSID), the AP in that BSS will respond by sending a Probe Response frame to the scanning STA. Once the scanning STA has processed any response, or has decided there will be no responses, it may change to another channel and repeat the process. At the conclusion of the scan, the STA has accumulated information about the BSSs in its vicinity.

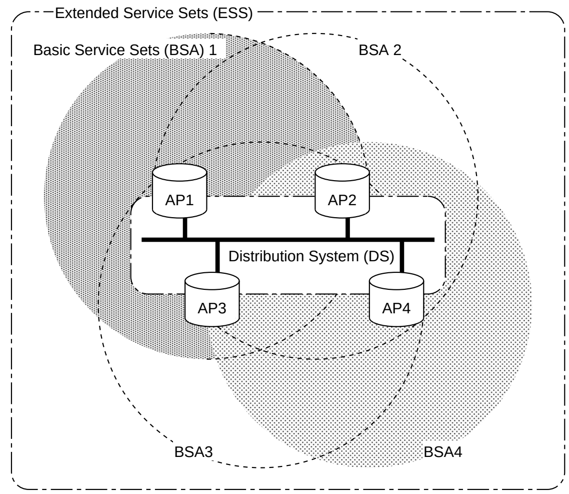

Fig. 1. Extended Service Set

After compiling these scan results, a STA can select one of the BSSs, and establish the association with the selected BSS. However, the AP selection is an implementation-specific decision, and most vendors currently implement as follows:

- The STA stores the received signal strength indicator (RSSI) of Beacon or Probe Response Frames. After finishing the scanning procedure, the STA selects the AP with the maximum RSSI.
- The STA continuously monitors the quality of the RSSI from other APs after establishing the association with selected AP. When the STA recognizes that one of other APs would be a better choice, it initiates the re-association procedure. The information used to make that decision are also implementation matter.

This AP selection strategy using RSSI leads to the concentration of many STAs in a few APs, as mentioned above. This overload of the AP will lead to both performance and fairness degradation and STAs cannot use the resource of wireless LAN effectively. Therefore, we can say that the existing AP selection algorithm depending on the RSSI can cause the performance degradation and is not suitable in wireless LANs accommodating multiple APs. Nowadays, more sophisticated AP selection architecture is needed, and we propose it in this study.

3. Mechanisms for Decentralized AP Selection

Our decentralized AP selection mechanisms will be described below. We will examine some dynamic selection scheme as well as one-time selection one. The former allows each STA to dynamically change its accessing AP in response to changing condition of wireless link etc., and in the latter each STA selects its AP only once when entering the wireless LAN domain and does not change it until leaving there.

Moreover, there are many possible algorithms for selecting an AP, which can be regarded as optimal strategies for achieving some objective, although the widely deployed one simply selects AP with strongest signal, as mentioned previously. They can be different in their available information used for selection and their employing objective function to be maximized or minimized. Here, two types of fundamental algorithms will be treated in what follows.

3.1. AP selection Algorithms

In existing wireless LANs, each STA selects the AP with maximum RSSI because it can be expected to attain the high-speed transmission rate. It, however, can lead to the concentration of many STAs in a few APs because it can happen that many STAs are geographically near some specific AP, which is thus very likely to provide the maximum RSSI with many STAs. This will cause significant degradation of their throughput, as mentioned above.

Two types of algorithms will be proposed below. The first one assumes that the number of STAs currently communicating with each AP is available for each STA as well as the signal strength of each AP. The expected achievable throughput of STA itself is of major concern. The second one further assumes that, for each AP, the largest PER of STAs communicating with it is available, which will allow each STA to take into consideration of some fairness.

3.1.1. AP selection algorithm for Maximizing Local Throughput (MLT): Each STA first estimates its achievable throughput for each AP, and then selects the AP being expected to provide the maximum throughput. Namely, each of STAs tries to optimize its own throughput locally. This algorithm is referred to in short as the algorithm for MLT. From [1], transmission time t_T in order to transmit a packet of Data [bits] is given by:

$$t_T = RTS + CTS + \frac{Data(bits)}{Rate(b/s)} + ACK + DIFS + 3SIFS \quad (1)$$

We here define P as the PER (Packet Error Rate) in order to take into account of the wireless link condition between STA and AP. In this case, average transmission time T_w which is required for sending and receiving a packet correctly is given by:

$$T_w = t_T + \sum_{i=1}^{\infty} P^i \cdot (1-P) \cdot i \cdot t_T = \frac{t_T}{1-P} \quad (2)$$

If we assume the ideal case in which the probability of collision can be negligible, N STAs that communicate with an AP can evenly share the wireless access resources, so that throughput θ will be given by the following equation:

$$\theta = \frac{Data}{T_w} = \frac{Data \cdot (1-P)}{t_T \cdot N} \quad (3)$$

Eq. (3) simply depends on the following function for each AP when packets are of same size:

$$W_{MLT} = \frac{1-P}{N} \quad (4)$$

where P denotes the PER, which can be obtained from the received signal strength, and N denotes the number of STAs which currently communicate with the AP. In order to provide each STA with the additional information of N, APs should be slightly modified to add the information on the Probe Response and Beacon frames. Finally, the AP with the largest W_{MLT} will be selected.

3.1.2. AP selection algorithm for Avoiding APs with Larger PER (AALP): With AP selection algorithm for MLT, each STA considers only its own achieving throughput. However, the wireless resource should be shared equally among STAs if possible, and we thus propose one of algorithms concerning the throughput of other STAs, in particular the STA with lowest throughput, without deteriorating its own throughput so much. Namely, the STA tries to avoid an AP which accommodates the STA with low throughput, which is due to both a large number of STAs sharing the AP together with it and large PER. This algorithm is referred to in short as the algorithm for AALP. The STA selects the AP by use of the following weighted function:

(if $0.5 \le P_{max}$)

$$W_{AALP} = (\tfrac{1}{2}\sqrt{2(1-P_{max})} + 0.5) \cdot W_{MLT} \quad (5)$$

(if $P_{max} < 0.5$)

$$W_{AALP} = W_{MLT} \quad (6)$$

where P_{max} denotes the largest PER among ones of STAs communicating with same AP. The AP can obtain PER of each STA from the received signal strength. W_{MLT} is the weighted function and calculated from Eq. (3). Both Eq. (5) and Eq. (6) is a heuristic function. We examined a various types of functions as possible candidates, and have seen that the achievable throughput would deteriorate too much if we avoid AP including STA with relatively small P_{max} in a very sensitive manner. Thus, if P_{max} is small, e.g., smaller than 0.5, we just employ the MLT. Even when P_{max} is larger than 0.5, we select an AP without hurting the achievable throughput so much by moderating an effect of P_{max}, as in Eq. (5). Namely, the AALP considers a trade-off between achievable throughput and some kind of fairness. Eq. (5) and Eq. (6) is just a candidate, and can be further improved from different viewpoints.

In order for STA to calculate the weighted function W_{AALP}, the information of the N and P_{max} should be included on the Probe Response and Beacon frames. Furthermore, AP is supposed to measure the P_{max} and maintain the number of STAs communicating currently.

3.2. Dynamic AP Selection Mechanism

First, each STA independently selects an appropriate AP according to the algorithm described previously when entering a wireless LAN. Then, the AP selected first may become an inappropriate one for the STA because the circumstance of wireless LAN can change. Therefore, we propose a new mechanism in order to cope with the change in the condition of the wireless LAN.

As shown in Fig. 2, our dynamic selection mechanism has three states: search state, re-search state, and idle state. In the search state, a STA executes one of the proposed algorithms to all available APs at predetermined intervals, denoted by Search Interval (SI), but does not immediately roam and transits to the next re-search state if some other different AP is selected as an appropriate AP. In the re-search state, the STA re-executes the algorithm after some back-off time and will roam only if the AP is selected again. After roaming to the new AP, the STA transits to the idle state. Figure 2 illustrates the relationship among these states, and the dynamic selection mechanism is more precisely described as follows; each of the numbers on the figure corresponds to the number of items below.

(1) A STA has selected some AP as an appropriate one. The STA calculates the weighted function according to the algorithm at the interval of SI.

(2) If some new AP, denoted by AP_{new}, is selected as an appropriate one as a result of calculation of weighted function, the STA transits to re-search state and re-calculates the weighted function after *Backoff Time* that is determined by random variable in $[0,\ 1]$.

(3) If the AP_{new} is selected as an appropriate AP again after re-calculation, the STA actually roams to the AP_{new}, and transits to idle state.

(4) If the current AP is selected after re-calculation, the STA returns to the search state.

(5) If some other AP is selected, which is different from both the current one and the AP_{new}, the STA remains the re-search state. The newly selected AP is regarded as AP_{new}, and the STA re-calculates the weighted function after *Backoff Time*.

(6) After roaming to the new AP, the STA waits for the Idle Time (IT) in order to prevent the ping-pong effect, and returns to the search state.

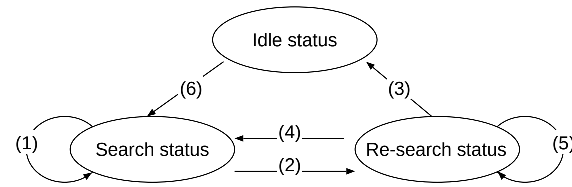

Fig. 2. The Dynamic AP Selection

4. Simulation Model

Our simulation model is illustrated in Fig. 3; a source (fixed host) communicates with 40 STAs via four APs. Each AP operates at a data rate of 11 Mb/s on different RF channels to prevent the interference among the APs. In addition, we use the shadowing model over the wireless link. Simulation experiments were performed by using the network simulator ns after modifying it to the 802.11b.

Sender $Source$ sends TCP packets to 40 STAs via $Router$ and four APs. The TCP variant employed here is TCP with SACK option [13], and its segment size is of 1,500 bytes. It is assumed that each TCP flow is used for greedy file transfer. The wired link between $Source$ and $Router$ is 10 Mb/s in bandwidth and 10 μsec in propagation delay, similarly the wired link between $Router$ and each AP is 100 Mb/s in bandwidth and 1 μsec in propagation delay. Each AP is located as shown in Fig. 4.

As mentioned previously, many STAs can join some specific AP and traffic load imbalance will thus happen among APs in reality. In order to take into account of this feature, we introduce three different areas in which STAs are located, as shown in Fig. 4; all of them are allocated uniformly in a rectangular area of 50m by 50m, 40m by 40m, and 30m by 30m, which are called Area 1, 2, and 3, respectively. In Area 1, STAs are most uniformly distributed to each of APs, while they are concentrated within a most limited area in Area 3, which provides most biased situation in terms of STAs' geographical location. Thus, Area 1 to 3 will be usually denoted by bias level of 1 to 3 in what follows. Arrivals of STAs are uniformly

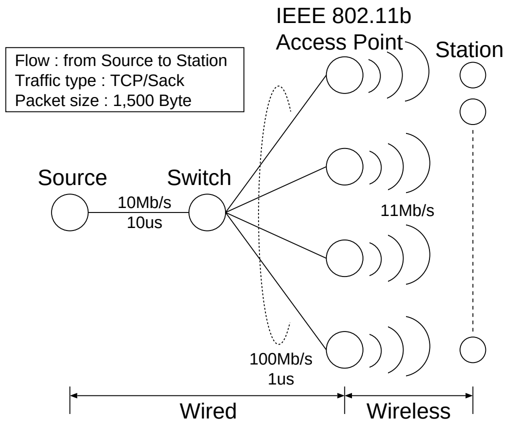

Fig. 3. Simulation Model

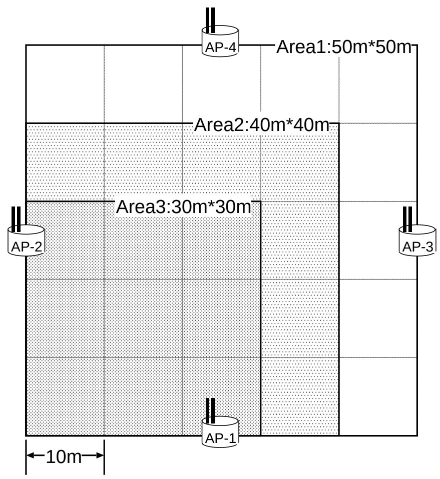

Fig. 4. Arrangement of APs

distributed over a period of 10 seconds. After all of 40 STAs are located within the wireless LAN, they will stay there during simulations.

As for AP selection algorithm, we use the following algorithm: (i) MLT, (ii) AALP, and (iii) RSS (Received Signal Strength), which is currently used in existing wireless LANs.

To quantify the performance of the proposed algorithm, we employ the throughput and the distribution of the average throughput as performance measure. In addition, we also use the balance index β introduced in [14] to reflect some fairness. Suppose B_i is the average throughput of STA i, then we define the balance index β to be:

$$\beta = \frac{(\sum B_i)^2}{(n \cdot \sum B_i^2)} \tag{7}$$

where n is the total number of STAs allocated in the simulation. The balance index has the property that it takes 1 when all STAs have exactly the same throughput and it gets closer to $1/n$ when throughput of STAs are heavily imbalanced.

5. Simulation Results and Discussions

We now present the simulation results. One-time AP selection scheme and dynamic AP selection scheme are treated below. In the former, each STA chooses some AP once when entering the wireless LAN and does not change it until leaving there. In the latter, each STA dynamically changes an AP to communicate with in response to changing situation. In each case, our two algorithms and the widely employed simple algorithm are examined.

In particular, we will see how our algorithms can improve the throughput characteristics from viewpoints of users and system managers. Users want provided throughput characteristics to be as much stable as possible, and do not expect their own throughput to be too small compared with one of others sharing the same wireless LAN. Thus, we will examine the minimum throughput among all STAs' ones and some index representing fairness. On the other hand, the system managers have to manage the wireless LAN in a way to use its resource efficiently, and the total throughput is one of major concerns, while they, of course, should satisfy users' requirements. As a result, a various types of TCP throughput will be focused as performance measure: total throughput of the wireless LAN, maximum STA throughput, minimum STA throughput, distribution of all STA throughput and balance index of throughput. In addition, we will treat three different types of Areas mentioned in the previous section in order to study how strongly imbalance of STAs' locations affects various throughput performance and how effectively our algorithms can resolve the issue arising from it.

5.1. One-time AP selection

Simulation experiments have been carried out for 250 seconds, and part of them, i.e., of 180 seconds from 70 to 250 seconds, is actually used to calculate the throughput in order to prevent the effect of the transient state of the TCP behavior.

The throughput characteristics obtained form simulations are illustrated in Tabs. I through III. As can be seen in these tables, the minimum throughput goes down with the increase of the bias level in all the algorithms. Since RSS algorithm uses only the signal strength to select the AP, imbalance of the number of STAs associated with APs can be so strong that the minimum throughput is, in fact, degraded to 154.73 Kb/s in Tab. III. On the other hand, MLT and AALP algorithms successfully alleviate throughput degradation in comparison with that of RSS. Furthermore, the minimum throughput of AALP is better than other algorithms in all cases. In the most strongly biased situation, i.e., bias level of 3, the minimum

TABLE I

THROUGHPUT IN BIAS LEVEL OF 1

algorithm	Throughput		
	minimum [Kb/s]	maximum [Kb/s]	total [Mb/s]
RSS	271.47	828.87	17.59
MLT	265.71	599.72	17.08
AALP	278.80	595.26	17.03

TABLE II

THROUGHPUT IN BIAS LEVEL OF 2

algorithm	Throughput		
	minimum [Kb/s]	maximum [Kb/s]	total [Mb/s]
RSS	206.52	1505.56	17.38
MLT	258.74	636.05	16.56
AALP	275.79	618.36	16.65

TABLE III

THROUGHPUT IN BIAS LEVEL OF 3

algorithm	Throughput		
	minimum [Kb/s]	maximum [Kb/s]	total [Mb/s]
RSS	154.73	2757.99	13.07
MLT	230.16	639.13	14.48
AALP	245.02	626.58	14.80

throughput of 245.02 Kb/s is achieved by AALP, whereas only 154.73 Kb/s by RSS. The minimum throughput is improved by approximately 100 Kb/s. Therefore, we can say that AALP can attain its object of preventing the STA with low throughput from getting worse by avoiding AP including it.

On the contrary, the maximum throughput of RSS increases with the increase of the bias level. In the bias level of 3, its maximum throughput becomes as much as 2757.99 Kb/s, which is very large compared with that of our algorithms. This is because only quite a few STAs happen to be located near by some specific AP and thus monopolize the transmission capacity of some APs. It can more likely happen with the increase of bias level. This can cause the unfairness in terms of achievable throughput of the STAs. As for the proposed algorithms, the maximum throughput is approximately 600 Kb/s and difference between the maximum and minimum throughput is small in comparison with that of RSS. Consequently, our algorithms can improve fairness in STA throughput.

Furthermore, RSS achieves higher total throughput in Tabs. I and II than MLT and AALP, while the reverse is true in Tab. III. In fact, AALP improves the total throughput up to 14.80 Mb/s from 13.07 Mb/s of RSS by 1.73 Mb/s. In particular, AALP is suitable in the context where STAs are much unevenly distributed over the wireless LAN, which can happen very likely. However, the total throughput of proposed algorithms should be further improved when STAs are rather evenly distributed, and it will be discussed in the dynamic AP selection

TABLE IV

BALANCE INDEX IN BIAS LEVEL OF 1 TO 3

algorithm	Balance Index		
	Area 1 50m by 50m	Area 2 40m by 40m	Area 3 30m by 30m
RSS	0.91	0.68	0.43
MLT	0.97	0.96	0.94
AALP	0.97	0.97	0.95

mechanism treated in the following subsection.

Next, we examine the fairness in throughput achieved by each of STAs by investigating both the distribution of average throughput and balance index in each algorithm. Figures 5 through 7 illustrate the distribution of average throughput in bias levels of 1 to 3. From these figures, the average throughput of MLT and AALP is distributed over a narrower range than that of RSS, which spreads over a wide range from quite low throughput to high one in Figs. 5 and 6. In particular, the average throughput of RSS is mostly lower than that of MLT and AALP in the bias level of 3. In order to more clarify the advantage of our algorithms, we show the survival function of the throughput in Fig. 8, which corresponds to Fig. 7, in the bias level of 3. From the figure, 50% of STAs achieve a throughput of more than 340 Kb/s in MLT and 350 Kb/s in AALP, respectively. In RSS, only 10% of STAs can attain the throughput of more than 300 Kb/s.

Finally, we examine the balance index to clearly show the fairness in STA throughput. Table IV shows the balance index in the bias level of 1 to 3. From Tab. IV, the balance indexes of MLT and AALP are always higher than that of RSS. In particular, they are still as much as 0.9 even when the bias level is 3, whereas the balance index of RSS decreases to approximately 0.4. Accordingly, the proposed algorithms can achieve high fairness in STA throughput even when STAs are unevenly distributed as in the bias level of 3. Consequently, we can say that the proposed algorithms can achieve high throughput and fairness in STA throughput compared with the existing algorithm in the case where the STA selects the AP only when they enter the wireless LAN.

5.2. Dynamic AP selection

Dynamic AP selection will be studied below, which was described in section 3. Each of STAs checks whether its current AP is still the best or not at some fixed search intervals. Our major concern is, first, the improvement in throughput performance achieved by the dynamic AP selection. Our attention should be paid to the related cost in parallel. When a STA roams from one AP to another AP, both of the APs will have to exchange some information on the STA, and will be thus very busy if roaming happens very often. Furthermore, packet loss may happen

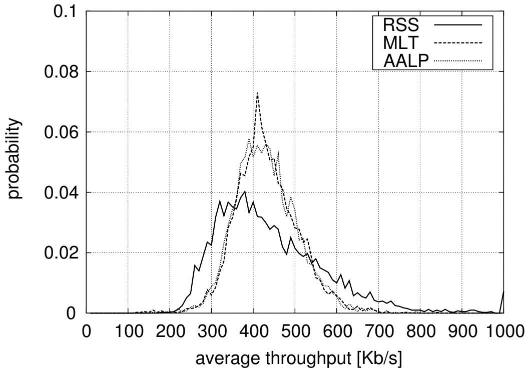

Fig. 5. Distribution of Average Throughput in Bias Level of 1

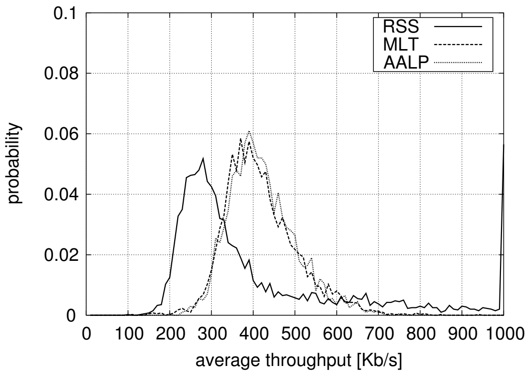

Fig. 6. Distribution of Average Throughput in Bias Level of 2

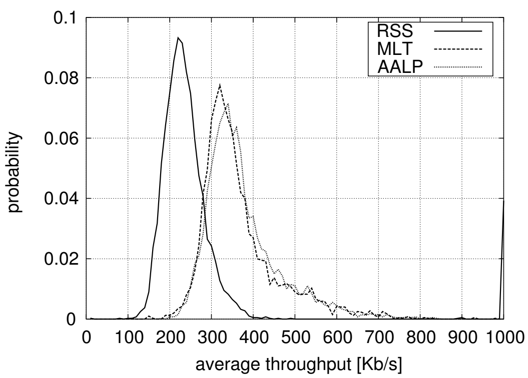

Fig. 7. Distribution of Average Throughput in Bias Level of 3

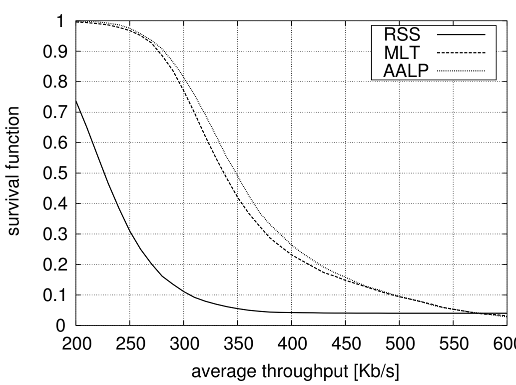

Fig. 8. Survival Function in Bias Level of 3

in process of roaming. We will thus have to examine how frequently roaming happens in some situation.

We perform the simulations under the same condition as that in the previous subsection, except that STAs employ the dynamic AP selection. From the above reasons, two types of states will be focused: transient and steady state. In the transient state, STAs enter the wireless LAN one by one, and keep roaming from one AP to another if they find better AP. Backoff Time to re-calculate the weighted function randomly varies within a range of $[0, 1]$ in this paper. If STAs no longer roam, the transient state ends and the state becomes steady. We investigate how many times roaming happens in the transient state. In addition, as in the previous subsection, various throughput performances will be obtained from simulations of 180 seconds from 60 to 240 seconds after the state becomes steady.

Figures 9 and 11 illustrate the average times of roaming as a function of search interval. Figures 10 and 12 show the period of transient state as a function of search interval. From Fig. 9, the average times of roaming in MLT is no more than 0.3, and decreases with the increase of search interval. Thus, many of STAs do not actually experience re-association with new APs. On the other hand, Figures 11 and 12 show that roaming happens very often in AALP. This is due to sensitivity of AALP to both the largest PER in an AP and the number of STAs sharing the AP. AALP is likely to be influenced by the change of the number of associated STAs. Furthermore, Backoff Time varies within a short range of [0, 1]. It can be further tuned.

From these results, it can be seen that MLT is superior in terms of the average times of roaming to AALP. Furthermore, the search interval of approximately 3 seconds in the MLT is suitable in our simulation in the sense that it can reduce the average times of roaming to some extent and prevent the period of transient state from increasing.

Next, we focus on the steady state. Tables V through VII show the throughput of each algorithm in the bias level of 1 to 3. As shown in Tabs. V through VII, throughput characteristics of each algorithm is significantly improved in comparison with Tabs. I through III. Consequently, we can say that the dynamic AP selection is very effective in improving both the minimum STA throughput and total throughput. Namely, the dynamic AP selection successfully overcomes the drawback of low total throughput of one-time AP selection. Furthermore, there is hardly any difference between the throughput performance of MLT and that of AALP, as shown in the tables. Actually, the survival function related with the average throughput shows that both of the algorithms provide almost the same performance, as shown in Fig. 13. We can say that MLT with dynamic AP selection is recommended from a viewpoint of its throughput performance and ease of implementation.

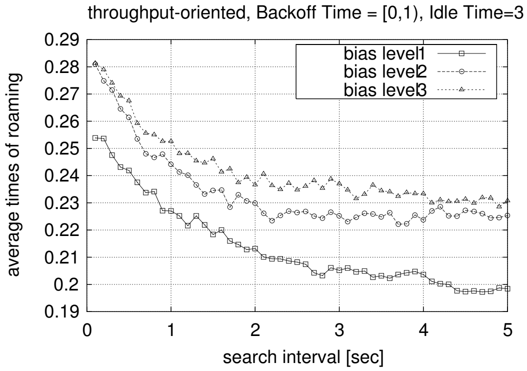

Fig. 9. Average Number of Roaming in MLT

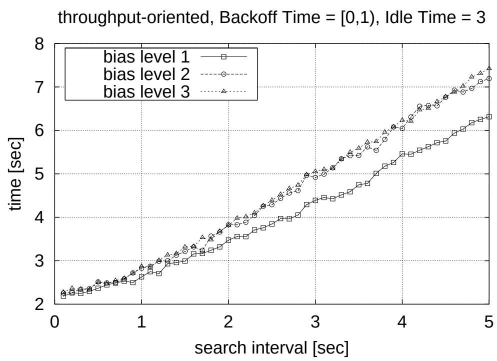

Fig. 10. Time for Transition in MLT

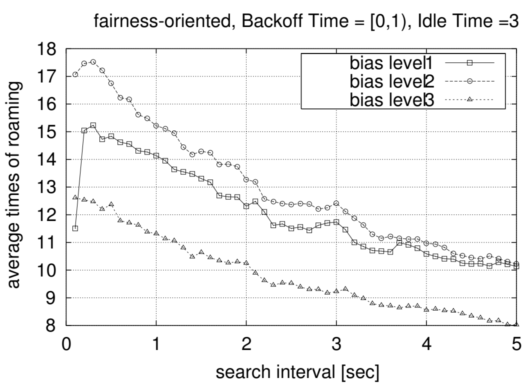

Fig. 11. Average Number of Roaming in AALP

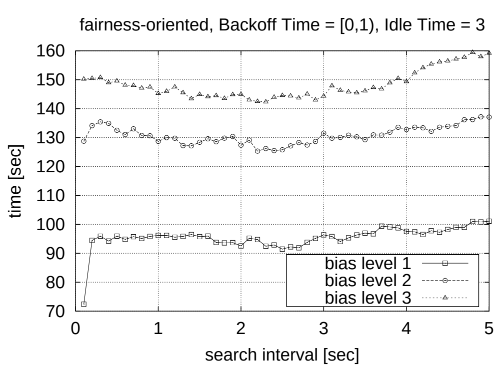

Fig. 12. Time for Transition in AALP

TABLE V

THROUGHPUT IN BIAS LEVEL OF 1

algorithm	Throughput minimum [Kb/s]	Throughput maximum [Kb/s]	Throughput total [Mb/s]
MLT	327.66	573.58	17.50
AALP	326.21	581.86	17.50

TABLE VI

THROUGHPUT IN BIAS LEVEL OF 2

algorithm	Throughput minimum [Kb/s]	Throughput maximum [Kb/s]	Throughput total [Mb/s]
MLT	308.99	599.20	17.10
AALP	315.29	596.80	17.12

TABLE VII

THROUGHPUT IN BIAS LEVEL OF 3

algorithm	Throughput minimum [Kb/s]	Throughput maximum [Kb/s]	Throughput total [Mb/s]
MLT	271.50	616.82	15.05
AALP	270.65	615.62	15.08

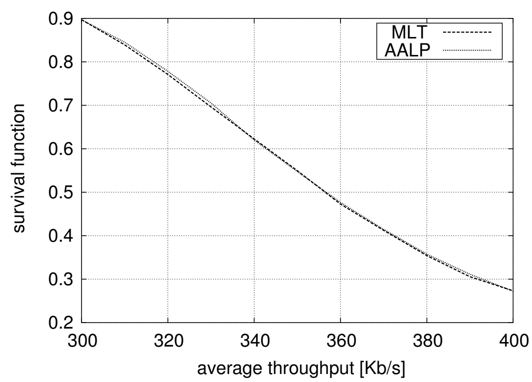

Fig. 13. Survival Function in Bias Level of 3

6. Conclusion

In this paper, we have particularly focused on the development of a decentralized way to enable each of STAs to select an appropriate one of available APs independently. Two types of algorithms have been proposed; MLT and AALP. In MLT, the expected achievable throughput of STA itself is of major concern. In AALP, each of STAs takes into consideration of some fairness. First, we have examined one-time selection, in which each STA selects its AP only once when entering the wireless LAN domain. From the simulation results, we have shown that proposed algorithms significantly improve both throughput and fairness in STA throughput compared with existing RSS when STAs are unevenly distributed. Next, we have examined dynamic AP selection mechanism, which allows each STA to dynamically change its accessing AP in response to changing condition. In this case, we have paid attention to the related additional management cost due to roaming as well as throughput performance. Therefore, we have focused on two types of states; one is transient state and another is steady state. In the transitional state, we have shown that MLT is superior in terms of the average times of roaming to AALP, and the search interval of approximately 3 seconds in the MLT is suitable in our simulation. As for AALP, there is a room for the improvement. Finally, in the steady state, we have shown that the dynamic AP selection is very effective in improving both the minimum STA throughput and total throughput. Furthermore, there is hardly any difference between the throughput performance of MLT and that of AALP. Therefore, we can say that MLT with dynamic AP selection is recommended from a viewpoint of its throughput performance and ease of implementation.

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References

[1] IEEE, "Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks-Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *IEEE Standard 802.11*, September 1999.

[2] Crow, B. P., Widjaja, I., Kim, J. G., and Sakai, P. T., "IEEE 802.11 Wireless Local Area Networks," *IEEE Communications Magazine*, Vol. 35, No. 9, pp. 116–126, September 1997.

[3] IEEE, "Supplement to IEEE standard for information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks-Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: High-speed Physical Layer Extension in the 5 GHz Band," *IEEE Standard 802.11*, September 1999.

[4] IEEE, "Supplement to IEEE standard for information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks-Specific requirements - Part 11: Wireless LAN Medium Access Control(MAC) and Physical Layer (PHY) Specifications: Higher-Speed Physical Layer Extension in the 2.4 GHz Band," *IEEE Standard 802.11*, September 1999.

[5] Tang, D. and Baker, M., "Analysis of a Loca-Area Wireless Network,", *In the Proceedins of ACM Mobicom 2000*, pp. 1–20, August, 2000.

[6] Tang, D. and Baker, M., "Analysis of a Metropolitan-Area Wireless Network,", *In the Proceedins of ACM Mobicom 1999*, pp. 12–23, August, 1999.

[7] Kotz, D. and Essien, K., "Analysis of a Campus-wide Wireless Network," *In Proceedings of the Eighth Annual International Conference on Mobile Computing and Networking*, pp. 107–118, September, 2002

[8] Balachandran,A., Voelker, G. M., Bahl, P., and Rangan, V., "Characterizing User Behavior and Network Performance in a Public Wireless LAN," *In the Proceedings of ACM SIGMETRICS'02, Marina Del Rey*, June, 2002.

[9] Balachandran, A., Voelker, G. M., and Bahl,P., "Hot-Spot Congestion Relief in Public-area Wireless Networks," *Proceedings of WMCSA'02*, Callicoon, NY, pp. 70–82, June 2002.

[10] O'Hara, B and Petrick,A., "802.11 Handbook A Designer's Companion," *IEEE Press*, 1999.

[11] Gast, M. S., "802.11 Wireless Networks: The Definitive Guide," *O'REILLY*, 2002.

[12] The VINT Project, Nework Simulator NS, *http://www.isi.edu/nsnam/ns/*.

[13] Mathis,M., Mahdavi, J., Floyd,S., and Romanow, A., "TCP Selective Acknowledgment Options," RFC2018, October 1996.

[14] Chiu, D. and Jain, R., "Analysis of the Increase and Decrease Algorithms for Congestion Avoidance in Computer Networks," *Computer Networks and ISDN Systems, vol. 17*, pp. 1–14, 1989.

[15] Tanenbaum, A. S., Ed., Computer Networks - Third Edition, Prentice-Hall International 1999.