

# Association Control for Throughput Maximization and Energy Efficiency for Wireless LANs

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**Abstract**—Because the access points (APs) and the stations (STAs) of a community network are deployed at the users' desired places, the APs and STAs tend to concentrate in certain areas. A concentration of STAs often results in the AP(s) and STAs in that particular area suffering from severe congestion. On the other hand, a concentration of APs causes energy wastage. A proper association control can effectively alleviate congestion and improve network throughput. In this paper, we analytically formulate the throughput maximization problem and show that the existing association control schemes do not necessarily maximize throughput. Furthermore, while load balancing tends to use all the existing APs, sufficient performance can be achieved by utilizing fewer APs, especially in AP-concentrated areas. This enables lower energy consumption by putting unused APs in power-saving mode. To this end, we propose an association control scheme that aims at maximizing network throughput and reducing energy consumption. Using both computer simulations and testbed experiments, we confirm that the proposed scheme provides excellent performance and that it is feasible using the off-the-shelf WLAN devices.

**Keywords**- association control, throughput maximization, congestion alleviation, energy efficiency

## I. INTRODUCTION

Due to the increasing popularity of WLAN technology, users (i.e., STAs) are often in the vicinity of one or more APs deployed at offices, school campuses, hotspot areas (e.g., cafes, train stations, airports), and individuals' homes. Such a widespread deployment of WLAN triggered a launch of community networks, including FON [1], which are built exploiting user-owned APs. As community networks enable users to enjoy ubiquitous Internet access, it has the potential to play an important role in the future networking paradigm.

The fundamental difference of community networks from e.g., enterprise wireless access networks is that the APs of a community network are deployed at the users' (i.e., the owners of the APs) desired places and they are generally not movable in a systematic manner. APs are often concentrated in areas such as a residential street, and their distribution is highly non-uniform. Figure 1 shows a FON map for an approximately 600m $\times$ 600m area in Tokyo (near Akihabara station) where 14 APs are installed in total. However, 8 APs are concentrated in a small area, approximately 1/8 of the overall area, in the upper left part of the map. In fact, the majority of these APs are deployed in a condominium building, which has residential homes, a café, conference spaces, and a fitness centre. The remaining 6 APs are installed in the rest of the overall area (approximately 7/8 of

the overall area). STAs (i.e., users) are, on the other hand, expected to be concentrated in public places, such as cafes and train stations. It is clear that STAs and APs are not necessarily concentrated in a same area. A concentration of STAs often results in the AP(s) and STAs in that particular area suffering from severe congestion [2]- [6]. On the other hand, a concentration of APs causes energy wastage [7].

Congestion can be effectively alleviated by proper association control. Indeed a large number of association control schemes are proposed for WLANs, mainly aiming at load balancing among cells under different definitions of load (e.g., load is defined as the number of nodes in [2], [3], channel condition in [4], and traffic rate in [5], [6]).

In this paper, we analytically formulate the throughput maximization problem, and show that the existing schemes do not necessarily operate towards throughput maximization. Furthermore, while load balancing tends to use all the existing APs, the same or even improved network performance can be achieved by utilizing fewer APs especially in AP-concentrated areas. This provides a positive impact on energy efficiency since the unused APs can now be in power-saving mode. To this end, we propose an association control scheme that is to maximize network throughput and reduce energy consumption. We investigate the efficiency and feasibility of the scheme by both computer simulations and testbed experiments.

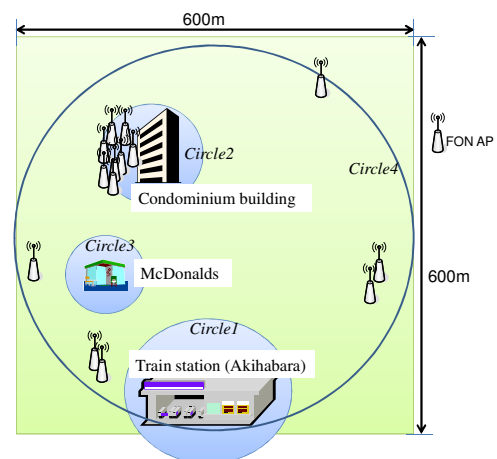


Figure 1. A map showing locations of FON APs in 600m $\times$ 600m area in Tokyo (the information is taken from maps.fon.com on July 20, 2010).

## II. PROBLEM FORMULATION AND RELATED WORK

The aggregate throughput of a DCF (Distributed Coordination Function) system is expressed as follows [8].

$$s = \frac{P_s P_{tr} E[P]}{(1 - P_{tr})\sigma + P_{tr}T} \quad (1)$$

Here,  $E[P]$  is the average data size,  $P_{tr}$  is the probability that there is at least one station transmits in the sensing range,  $P_s$  is the probability of a successful transmission.  $\sigma$  is the slot time and  $T$  is the average time required for transmission of a data (includes DIFS and etc.). The numerator of (1) corresponds to the successfully transmitted payload length and the denominator is the total time. The former and the latter components of the denominator are the time that channel is idle and busy (either due to successful or unsuccessful transmissions), respectively.

Data transmission is successful if the frame is not collided and the frame does not contain errors (due to poor link quality). Thus letting  $P_{sc}$  and  $P_{sc}$  represent the priorities of the former and the latter events, respectively,  $P_s = P_{sc} \times P_{sc}$ .  $P_{sc}$  (in what follows we call  $P_{sc}$  as success probability) is expressed as

$$P_{sc} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}, \quad (2)$$

where  $n$  is the number of nodes.  $\tau$  is the channel access probability, which is determined by the contention window size (CW) and the probability that a node has a pending packet in its transmission queue [9]. Letting  $r = P_{sc} \times E[P]/T$ , we rewrite (1) as

$$s = P_{sc} \times r \times \frac{P_{tr}T}{(1 - P_{tr})\sigma + P_{tr}T} \quad (3)$$

$E[P]/T$ , the average frame transmission rate, is variable if rate adaptation is deployed at MAC, and it is fixed otherwise. If rate adaptation is deployed, the better the link quality (stronger RSSI), the higher is the selected transmission rate. Furthermore, if the rate adaption operates such that PER is minimized (i.e.,  $P_{sc}$  is maximized), the second component of (3),  $r$ , depends mainly on the selected transmission rate, i.e.,  $r \approx E[P]/T$ . The last component of (3) is the ratio of time the channel is determined to be busy to the total time. Letting ATR (air-time ratio) represent the last component, the throughput of a DCF system is a multiplication of  $P_{sc}$ ,  $r$ , and ATR:

$$s = P_{sc}(n) \times r(\text{RSSI}) \times \text{ATR} \quad (4)$$

Finally, the throughput maximization problem for a network that consists of multiple overlapping WLANs is the maximization of

$$S = \sum_{i=1}^N s_i, \quad (5)$$

where  $s_i$  is the throughput of cell  $i$ . It should be noted that overlapping cells, which operate under a same frequency channel, share the same  $P_{sc}$  and ATR.

In the traditional AP selection policy, a STA associates with the AP corresponding to the strongest RSSI. Thus such a scheme takes account of only the second component of (4),  $r$ . However, increasing  $r$  alone does not necessarily increase the total throughput, especially when STAs' distribution is highly non-uniform. In such a scenario, it is possible that

most of the STAs select a same AP (because they are closer to that AP). As it can be seen in (2),  $P_{sc}$  decreases sharply with the increase of  $n$  (because the numerator of approaches zero and denominator approaches 1). Thus, in such a case, the throughput of the traditional scheme is poor because of a small  $P_{sc}$  for the crowded cell(s) and likely a small ATR for the scarce cell(s). This suggests distributing STAs to the existing cells. Indeed several schemes are proposed to distribute the number of STAs among cells, and some of them take account of the link quality (RSSI in [2], and PER in [3]). A drawback of these schemes is that they do not consider ATR, the channel availability.

Since DCF requires some idle slots for e.g., backoff procedures, ATR is upper-limited by a value smaller than 1 (let  $\text{ATR}_{\max}$  represent the saturation value). Furthermore, it has been recognized that ATR has an optimal value,  $\text{ATR}_{\text{th}}$  ( $\text{ATR}_{\text{th}} < \text{ATR}_{\max}$ ), where the channel utilization is maximized [10]. This means that  $P_{sc}$  is maximized when ATR is equal to or smaller than  $\text{ATR}_{\text{th}}$ .

Reference [4] proposed to balance effective channel busy-time (i.e., time the channel is busy for successful transmissions) among cells. Because it does not discriminate the time corresponding unsuccessful transmissions and the idle time, [4] may suffer from such estimation errors. Moreover, because [4] ignores offered traffic volume, it might take a long time until load is balanced.

ATR is also the ratio of the amount of bandwidth consumed for transmissions to the total bandwidth. Thus, an increase of the offered traffic volume (injected traffic) increases ATR until it reaches its saturation value ( $\text{ATR}_{\max}$ ). Further increase of the offered traffic, however, results in congestion (i.e., buffer overflow) that significantly hampers communication performance. Since a cell with a small ATR can accommodate additional traffic, the overall throughput can be improved by moving STAs from a congested cell to such a non-congested cell. References [5], [6] proposed schemes that balance traffic volume among cells. A drawback of the schemes is that they do not consider the fact that the overlapping cells operating under the same frequency channel share the same channel resource. Moreover, [4]-[6] do not consider the link quality (the second component of (2)), and thus they may force STAs to use links with poor quality, degrading the users' throughput. To the best of our knowledge, none of existing schemes takes account of the overall of (4), thus they do not necessarily maximize throughput. To this end, we propose an association control scheme that takes account of the overall of (4). The direct target of the proposed scheme is maximizing the sum of the multiplication of the second and third components of (4),  $r$  and ATR, by taking account of RSSI, ATR, and the offered traffic volume. The success probability,  $P_{sc}$ , is indirectly maximized by maintaining ATR smaller than  $\text{ATR}_{\text{th}}$ . An important difference of the proposed scheme from the previous schemes is that because both the offered traffic and channel availability are estimated for each cell, the proposed scheme does not aim at load balancing. This enables the scheme to utilize fewer APs, providing a positive impact on energy efficiency.

### III. PROPOSED SCHEME

A user-owned AP is integrated into a community network by a common equipment/software program provided by the entity (e.g., FON [1]). Besides integrating users' APs, the entity can play an important role for e.g., network management for better communication quality. Hence, community networks are centrally controllable and we expect that the members (i.e., the users) are cooperative to such a control. To this end, while a distributed mechanism can also be designed, we propose a centralized association control scheme due to ease of management and better performance [4]-[5], [7]. The proposed scheme aims at maximizing network throughput by a congestion alleviation mechanism and reducing energy consumption by a cell aggregation mechanism. For a large community network, the network can be divided into sub-networks, which are independently and separately controlled.

Figure 2 shows the network architecture. Besides APs and STAs, the network has an information server (server) and control manager (manager). The server and manager can be physically separated or coexist in a same machine. APs and STAs periodically inform the server of information on link quality and so on. Periodically referring to the information, the manager triggers STAs' handover for improved network throughput and/or energy efficiency.

#### A. Estimation of Channel Availability and Offered Traffic

STAs and APs measure RSSI, ATR, and the offered traffic volume, and inform the server of the information. The manager uses the information to estimate channel availability and traffic condition for each cell, and changes STAs' associations.

##### ♦ Frame Transmission Rate

By periodically performing channel scanning, STAs learn the existence of the neighboring APs and the corresponding  $RSSI_{AP,STA}$ . Such background scanning is supported by the off-the-shelf wireless LAN cards [11], and some efforts have been made for fast channel scanning [12]. Transmission rate for frame payload field is estimated from  $RSSI_{AP,STA}$  and finally the frame transmission rate,  $r_{AP,STA}$  ( $\approx E[P]/T$ ), for each pair of STA and AP is calculated.

##### ♦ ATR

For ease of implementation and without much loss of generality, ATR can be defined as the ratio of the channel busy time to the total time (the numerator does not contain inter-frame spaces (DIFS, SIFS)). In the proposed scheme, each AP measures ATR on its operating channel. Such a measurement can easily be made using the existing WLAN cards [4],[7],[13]. We empirically found that the appropriate values for  $ATR_{max}$  and  $ATR_{th}$  are 0.6 and 0.58, respectively.

##### ♦ Potential Throughput

The manager estimates the maximum achievable throughput for each pair of STA and its neighboring AP (which is not the STA's currently associated AP). Let  $PT_{STA,AP}$  (potential throughput) represent the maximum achievable throughput for such a STA and an AP. As (4) shows, the throughput is a function of  $P_{sc}$ , the estimated transmission rate ( $r_{AP,STA}$ ), and  $ATR_{AP}$ .

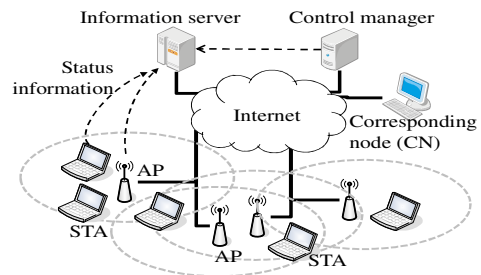


Figure 2. Network architecture.

As discussed in the previous section, however,  $P_{sc}$  can be maximized by ensuring  $ATR$  below  $ATR_{th}$ . This enables  $PT$  be estimated from only  $r_{AP,STA}$  and  $ATR_{AP}$ . Thus the manager calculates  $PT$  for each STA and its neighboring AP as

$$PT_{AP,STA} = \begin{cases} 0, & ATR_{AP} \geq ATR_{th} \\ (ATR_{th} - ATR_{AP}) \times r_{AP,STA}, & \text{otherwise} \end{cases} \quad (6)$$

The upper equation is to not move the STA to the AP because  $ATR_{AP}$  exceeds  $ATR_{th}$ . Otherwise, the AP is a candidate destination AP for the STA and the maximum achievable throughput at the candidate cell is expressed as the lower equation. In our previous work [13], we confirmed that such an estimation of  $PT$  can be achieved with a high accuracy using the existing WLAN cards.

##### ♦ Offered Traffic

A STA can be moved to a neighboring AP, if it does not cause congestion at the neighboring cell. The condition can be checked by comparing the offered traffic volume for the STA and  $PT_{STA,AP}$  (to be discussed later). Letting  $EnqueueRate_{A,B}$  be the rate at which packets destined to node B are inserted into the IP queue at node A, the offered traffic volume for a STA is defined as

$$OfferedRate_{STA} \equiv EnqueueRate_{STA,AP} + EnqueueRate_{AP,STA} \quad (7)$$

If the WLAN is the bottleneck link of the end-to-end route, the OfferedRate is approximately equal to the traffic generation rate.

#### B. Congestion Alleviation

A cell is considered to be congested if

$$ATR > ATR_{th} \quad (8)$$

If the condition (8) is met for a cell, the manager checks if the aggregate offered rate exceeds the aggregate packet throughput for that cell, i.e.,

$$\alpha \sum_{STAs} OfferedRate_{STA} > \sum_{STAs} PacketThroughput_{STA} \quad (9)$$

Here  $\alpha (<1)$  is a system parameter to absorb rate fluctuation.  $PacketThroughput_{STA}$  is the sum of the rates at which packets are successfully transmitted on the uplink and downlink for the STA. The condition (9) indicates that one or more nodes in the cell are suffering from buffer overflow. It is possible that a cell satisfies (8) but not (9), in a case, when the cell does not have much traffic but the channel is congested due to the overlapping cells.

A cell that satisfies both (8) and (9) becomes a target cell of congestion control. Letting  $APT$  be the AP of the target

cell, the manager selects STAs to move from APt to its neighboring cells. The association control is made based on the following policies:

1. Moving STAs are selected such that the number of handovers is minimized.
2. A STA should be moved only if it will not cause congestion at the destination cell.
3. Among the candidate destination APs, the STA should be moved to the AP corresponding to the strongest RSSI.

The more the handovers, the larger is the control overhead. Thus policy 1 is to minimize the number of moving STAs. To support this objective, we define "load" of a STA, as  $Load_{STA} \equiv OfferedRate_{STA} / TxRate_{STA, APt}$ . Here  $TxRate_{STA, APt}$  is the rate used for transmissions of frame payload fields between the STA and APt. Obviously, the larger the offered traffic and/or the lower the transmission rate, the heavier loaded is the STA for APt. Due to policy 1, heavier loaded STAs are preferred to be moved from APt over lighter loaded STAs. For policy 2, a STA is moved to a neighbouring AP, APd, only if the condition (10) is met.

$$OfferedRate_{STA} < PT_{STA, APd} \quad (10)$$

In other words, the STA is moved to APd only if the destination cell can accommodate the offered traffic volume for the STA. Finally, among the candidate destination APs (i.e., the APs that satisfy (10) for the STA), the AP corresponding to the strongest RSSI is selected as the destination AP for the STA.

When a STA,  $STA_m$ , is selected to be moved from APt, the manager updates the aggregate offered rate (see (9)) for the target cell by decrementing it by  $OfferedRate_{STA_m}$ . Moreover ATR for the destination cell and its overlapping cells (which operate using the same channel) is incremented by  $OfferedRate_{STA_m} / r_{APd, STA_m}$ . After updating the values, the manager checks if the target cell still satisfies (9). If it does, the manager selects the next moving STA.

- Discussion on TCP traffic

TCP reacts to congestion and controls its rate based on AIMD algorithm. However such a rate change occurs in the order of RTT (milliseconds) which is much shorter than the control period at the manager (in order of seconds). Therefore we expect that the proposed scheme does not react to the AIMD-based rate fluctuation, but only the gradual change of the average rate. Hence, the proposed scheme and TCP can stably coexist. Moreover because TCP adjusts its traffic rate,  $OfferedRate_{STA}$  for STA might be largely changed due to the STA's movement. However, it should be reminded that a STA is moved to a neighbouring cell only if the destination cell can accommodate the current  $OfferedRate$  for the STA (see (10)). Thus we expect that TCP throughput will be increased or maintained after the STA's movement. Furthermore, since some amount of channel resource is released at the previous cell of the moving STA, STAs in that cell can now increase their rate.

### C. Cell Aggregation

Since both of the offered traffic volume and the channel availability are known for each cell, load balancing among

cells is not necessary. Indeed, if all the associated STAs of an AP can be moved to its neighboring cells without hampering the network throughput, such STA movements should be encouraged for energy efficiency, since the AP can now be in power-saving mode. Our scheme can provide such an association control based on the following policies:

1. The target AP is an AP that is associated with preferably a few STAs, which can all be moved to the neighboring cells.
2. To suppress channel interference, the target AP should have overlapping cells that operate using the same frequency channel.
3. Policy 2 described in the previous subsection.
4. Policy 3 described in the previous subsection.

The manager triggers a handover only if destination APs are found for all the STAs of the target AP. A detailed protocol design for actually putting APs in power-saving mode is left for our future work. The main concern of such a protocol design is to ensure newly arriving STAs are covered by the network. For such a control, Wake-on-WLAN technology [14] can be used.

### D. Changing STA's Association

To change a STA's association, the manager sends a control frame to the STA, indicating the destination AP and the corresponding channel information. Such a network directed association control can be supported by the upcoming IEEE 802.11v [15], which enables APs to explicitly request STAs to re-associate with an alternate AP.

## IV. PERFORMANCE EVALUATION

### A. Simulation Evaluations

Using Scenargie network simulator [16], we investigate the proposed scheme with and without cell aggregation capability. The performance of the proposed scheme is compared against:

- Strongest RSSI: The traditional AP selection scheme.
- LB(NumofSTAs): A load balancing scheme [2], which takes account of the number of STAs and RSSI.
- LB(Traffic): A load balancing scheme [5], where load of a cell is defined by traffic rate.

In each scheme, STAs initially associate with APs based on the strongest RSSI policy. In the proposed scheme, STAs inform the server of the measured information using a 160 bytes packet. The manager checks the collected information in every 1s. 20-bytes of packets are used for handover requests and replies between the manager and moving STAs.  $\alpha$  (see (9)) is set to 0.98.

Performances of the schemes are investigated for the real-world scenario depicted in Figure 1, where 14 APs are non-uniformly distributed in a 600mx600m area. 8 APs are concentrated in the small area (around the condominium), the other 6 APs are installed in the remaining area as shown in the figure. The network operates using IEEE 802.11a [17], where 3 orthogonal frequency channels are available. Frequency channel allocation (to the APs) is made based on a simple graph coloring technique.

STAs (users) can be anywhere, but it is natural to expect that users are especially attracted to the public places specifically, the train station, condominium building (for the café), and McDonalds in the target map. Thus, in our simulations, 40 STAs are distributed in the circle-shaped areas centered at the 1) train station, 2) condominium building, 3) McDonalds, and 4) the center of the map, with a radius of 100m, 10m, 10m and 300m, respectively (see Figure 1). The first three areas are set to create users' concentration in the public places, while the last area is for uniform distribution of users in the overall area. Table I shows the simulation scenarios, which have different number of STAs in each circle-shaped area. The smaller the scenario number, the more uniform is the STAs' distribution.

Figures 3 and 4 show the results of the simulations targeted at TCP and UDP traffic, respectively. In TCP simulations, STAs upload 5MB of file using FTP/TCP-SACK. In UDP simulations, STAs have uplink and downlink CBR traffic generated at a random rate in the range of [0Mbps, 1.2Mbps].

As the figures a) show, for both the TCP and UDP traffic, the performance of Strongest RSSI scheme is inferior to the remaining schemes and the proposed scheme shows the best performance. The proposed scheme with the cell aggregation mechanism achieves around the same throughput performance as the scheme without cell aggregation especially for UDP traffic. The load balancing schemes have lower throughput than that of the proposed scheme, because they do not take account of the overall of (4).

The figures a) show that, for any scheme, the throughput tends to be smaller when STAs' distribution is less uniform (e.g., the throughput of S7 is smaller than that of S5). As discussed in Section II, the reason is clear for the strongest RSSI scheme (many STAs select the same AP). The reason for the remaining schemes is as follows. When STAs are highly concentrated around a particular AP, the schemes have to move some of the STAs to farther APs. This reduces the frame transmission rate,  $r$ , for the moving STAs, resulting in lower throughput compared to that of a scenario where STAs' distribution is more uniform. Nevertheless, compared with the strongest RSSI scheme, the overall throughput is improved due to an increase of the 1<sup>st</sup> and 3<sup>rd</sup> components of (4). Finally, S1 (where STAs' distribution is uniform), however, does not show the largest throughput due to the non-uniform AP distribution.

Figures 3b) and 4b) compare the number of active APs, i.e., the number of APs that actually serve for the users. As the figures show, the load balancing schemes use all the existing APs (except in scenario S7, where STAs are concentrated only at the train station). Strongest RSSI scheme, on the other hand, does not use many APs due to its simple AP selection policy. The proposed scheme without cell aggregation utilizes around the same number of APs as that of Strongest RSSI scheme. Finally, the scheme with cell aggregation utilizes the smallest number of APs. This is especially attractive because, compared to the existing schemes, the proposed scheme largely improves throughput while utilizing fewer APs. Our future work includes a study

on how much energy reduction can be achieved by such an association control.

TABLE I. SIMULATION SCENARIOS (USER DISTRIBUTION)

	Circle1 (station)	Circle2 (condominium)	Circle3 (McDonalds)	Circle4 (overall area)
S1	0	0	0	40
S2	10	10	10	10
S3	10	20	0	10
S4	10	20	10	0
S5	20	10	0	10
S6	30	0	0	10
S7	40	0	0	0

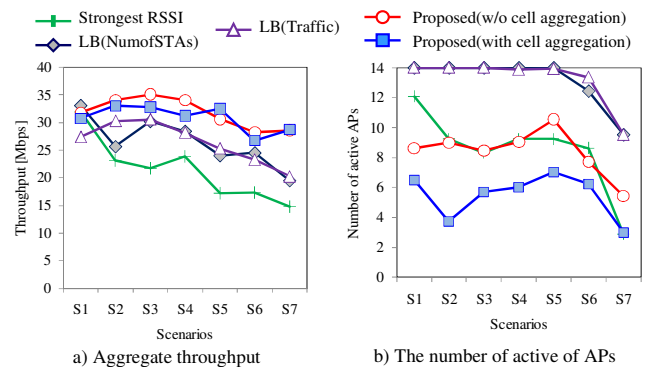


Figure 3. Performance comparison for TCP traffic.

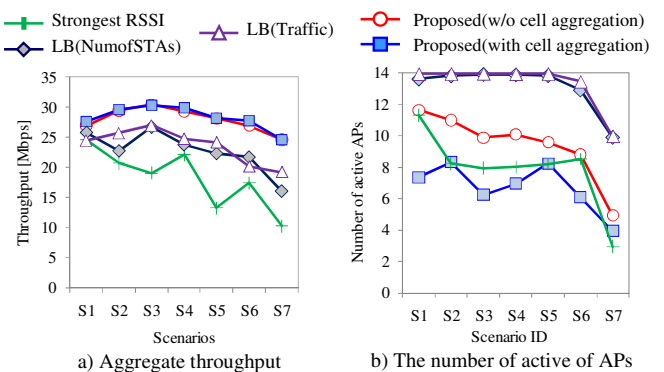


Figure 4. Performance comparison for UDP traffic.

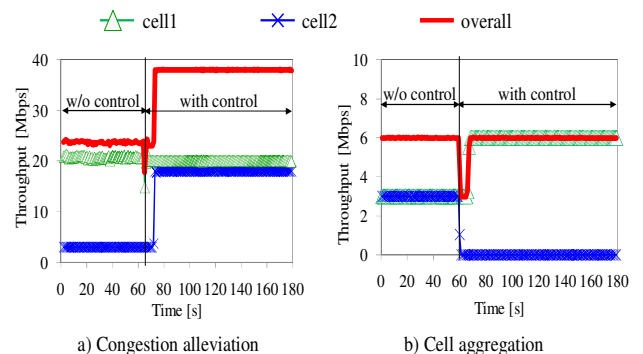


Figure 5. Empirical results.

### B. Testbed Evaluations

We implemented the proposed scheme in a wireless testbed and evaluated its throughput performance. Computers with Cent OS 5.5 (kernel 2.6.25-17) are used for STAs, APs, and the manager (note that the manager and server coexist in a same machine). The APs, the manager, and a source computer (acts as a corresponding node (CN)) are connected to a 100Mbps Ethernet. The APs and STAs are equipped with 802.11a WLAN card made by NEC (Aterm WL54AG). We modified the Atheros device driver to enable measurements of ATR and PacketThroughput (see (9)). The packet transmission rate from the kernel to the device driver is monitored to measure EnqueueRate (see (7)). TCP is used for information collection at the server and for handover requests and replies. The testbed evaluations target scenarios that consist of 2 APs, AP1 and AP2, which use different frequency channels and are each initially associated with 3 STAs. An experiment lasts about 200 s. Two scenarios (scenario1 and 2) are set to evaluate the congestion alleviation and cell aggregation mechanisms. In scenario1, CN transmits 15, 10, and 10 Mbps CBR traffic to the STAs, which are initially associated with AP1, and 1Mbps traffic to each STA initially associated with AP2. For scenario 2, CN transmits 1Mbps CBR traffic to each STA. To see the impacts of the proposed mechanisms, the manager is activated at app. 60 s for both the scenarios.

Figure 5 shows the time series plots of the throughput for the scenarios. In Figure 5a), when the manager is not activated, the aggregate throughput is 22Mbps and packet loss ratio is app. 40%. Upon the activation of the manager, the STA with 15 Mbps traffic is moved to cell2. This association control maximizes the throughput (aggregate throughput is 38Mbps) and eliminates packet loss ratio. For scenario 2 (see Figure 5b)), as both the cells are lightly loaded, congestion is not an issue, thus the system shows 6Mbps throughput and 0% of packet loss ratio even before the activation of the manager. Upon the activation of the manager, the cell aggregation is performed and all the STAs of cell2 are moved to cell1.

Unfortunately, as it can be seen in the figure, it took app. 6 seconds to complete the handover (without depending on the number of moving STAs). The 6 seconds are used for 1) MAC layer disassociation/association, 2) IP route advertisement, 3) IP duplicate address detection, 4) MIP binding update, and 5) MIP binding acknowledgement. Among the operations, there was a software bug corresponding to 2) and we confirmed that by fixing this bug, handover time can be reduced down to 3 seconds. We are now working on this issue.

### V. CONCLUSION

In this paper, we analytically formulated the throughput maximization problem for WLANs and showed that the existing association control schemes do not necessarily maximize network throughput. Furthermore, since most of the existing schemes aim at load balancing among cells, they tend to use all the existing APs. However, sufficient network performance can be achieved by utilizing fewer APs,

providing positive impact on energy efficiency. To this end, we proposed an association control scheme to maximize throughput and reduce energy consumption. The simulation results showed that compared to the existing schemes, the proposed scheme can provide much larger throughput while utilizing fewer APs regardless of traffic type and node density. The testbed experiment shows that proposed scheme is feasible using the off-the-shelf wireless LAN cards. Our future work includes a study on energy efficiency induced by the cell aggregation mechanism.

### ACKNOWLEDGMENT

This research was performed under research contract of "Research and Development for Reliability Improvement by The Dynamic Utilization of Heterogeneous Radio Systems", for the Ministry of Internal Affairs and Communications, Japan.

### REFERENCES

- [1] FON, [www.fon.com](http://www.fon.com)
- [2] S. Sheu and C. Wu, "Dynamic Load Balance Algorithm (DLBA) for IEEE 802.11 Wireless LAN," *Tamkang Journal of Science and Engineering*, vol. 2, no. 1, pp.45-52, 1999.
- [3] Y. Fukuda and Y. Oie, "Decentralized Access Point Selection Architecture for Wireless LANs," *IEICE Trans. Commun.* vol. E90-B, no. 9, pp. 675-684, 2007.
- [4] F. Guo and T-C. Chiueh, "Scalable and Robust WLAN Connectivity Using Access Point Array," *IEEE DSN'05*, pp. 288-297, 2005.
- [5] I. Jabri, N. Krommenacker, T. Divoux, and A. Soudani, "IEEE 802.11 Load Balancing: An Approach for QoS Enhancement," *Springer, Int J Wireless Inf Networks*, vol 15, pp.16-30, 2008.
- [6] H. Velayos, V. Aleo, and G. Karlsson, "Load Balancing in Overlapping Wireless LAN Cells," *IEEE ICC 2004*, Vol. 7, pp. 3833-3836, 2004.
- [7] A. J. Jardosh, K. Papagiannaki, E. M. Belding, K. C. Almeroth, G. Iannaccone, and B. Vinnakota, "Green WLAN: On-demand WLAN Infrastructures," *Springer, Mobile Networks and Applications*, Vol. 14, No. 6, pp. 798-814, Dec. 2008.
- [8] G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function," *IEEE Journal on Selected Areas in Comm.*, vol. 18, no. 3, pp. 535-547, March 2000.
- [9] F. Daneshgaran, M. Laddomada, F. Mesiti, and M. Mondin, "Unsaturated Throughput Analysis of IEEE 802.11 in Presence of Non Ideal Transmission Channel and Capture Effects," *IEEE Trans. Wireless Comm.* vol. 7, issue: 4, pp. 1276 – 1286, April 2008.
- [10] H. Zhai, X. Chen, and Y. Fang, "How well can the IEEE 802.11 Wireless LAN support Quality of Service," *IEEE Trans. Wireless Comm.* Vol. 4., no. 6, pp. 3084-3094, Nov. 2005
- [11] <http://madwifi.org/>
- [12] I. Ramani and S. Savage, "SyncScan: practical fast handoff for 802.11 infrastructure networks," *INFOCOM 2005*, Vol.1, pp. 675-684, 2005.
- [13] S. Tang, N. Taniguchi, O. Shagdar, M. Tamai, H. Yomo, A. Hasegawa, and et al., "Potential Throughput Based Access Point Selection," *IEEE APCC 2010*.
- [14] IEEE 802.11v: Wireless Network Management, [http://grouper.ieee.org/groups/802/11/Reports/tgv\\_update.htm](http://grouper.ieee.org/groups/802/11/Reports/tgv_update.htm).
- [15] N. Mishra, K. Chebroulu, B. Raman, and A. Pathak, "Wake-on-WLAN," *ACM, WWW*, pp. 761-769, 2006.
- [16] Scenargie, <http://www.spacetime-eng.com>
- [17] IEEE Computer society LAN MAN Standards Committee, Wireless LAN Medium Access Protocol (MAC) and Physical Layer (PHY) Specification, IEEE Std 802.11-1997, IEEE, 1997.