

# Optimizing Multicast Performance in Large-Scale WLANs\*

Ai Chen, Dongwook Lee, and Prasun Sinha

Department of Computer Science and Engineering, The Ohio State University  
email: {chenai, leedon, prasun}@cse.ohio-state.edu

## Abstract

*Support for efficient multicasting in WLANs can enable new services such as streaming TV channels, radio channels, and visitor's information. With increasing deployments of large-scale WLANs, such services can have a significant impact. However, for a solution to be viable, the multicast services must minimally impact the existing unicast services which are currently the core services offered by most WLANs. This paper focuses on three objective functions motivated by different revenue functions and network scenarios: maximizing the number of users (MNU), balancing the load among APs (BLA), and minimizing the load of APs (MLA). We show that these problems are NP-hard and present centralized approximation algorithms and distributed approaches to solve them. Using simulations we evaluate the performance of these algorithms. We observe that the number of users can be increased by up to 36.9%, and the maximum AP load and the total load can be reduced by up to 52.9% and 31.1%, respectively.*

## 1 Introduction

The goal of anytime-anywhere connectivity is becoming a reality with increasing deployment of large scale campus-wide and even city-wide Wireless LANs. While unicast services are essential for providing Internet access to individual users through WLANs, efficient multicast support from the network can be leveraged for distribution of stored or live multimedia content, such as local news, visitor's information, and local TV channels. While introducing media-rich multicast streaming in WLANs, it is critical to ensure that the multicast services use the resources efficiently and the unicast services get minimally effected. However, the current IEEE 802.11 standard can not efficiently maximize resource usage, since uncontrolled association causes multiple access points (APs) with overlapping regions to redundantly transmit the same multicast packets, thereby wasting resources for unicast services. *In this paper, we study how to provide efficient multimedia multicast service to users by controlling the user-to-AP association in WLANs.*

Although association control has already been considered by both the research community and the industry, pre-

vious research on association control in WLANs primarily focused on unicast traffic [1, 5, 11]. In [5, 11], new metrics are studied to associate with APs instead of signal strength for only unicast traffic. These works do not consider load-balancing between APs. Recent work [1] has explored the idea of association control to balance the network load and provide max-min fairness among users. However, their study is limited to unicast traffic. *To the best of our knowledge, we are the first to study the association control for enabling efficient multicast streaming services in WLANs.*

We study three different objectives — **Maximizing the Number of Users (MNU)**, **Balancing the Load among APs (BLA)**, and **Minimizing the Load of APs (MLA)** — supported by different revenue functions that can be used by the WLAN service provider depending on the expected network scenario. We make the following contributions. First, we show the NP-hardness of the three problems even if we restrict the problem so that multicast/broadcast packets are always transmitted at the basic rate. Second, we reduce the three problems to other known problems and present centralized approximation algorithms. For MNU, MLA and BLA, we present approximation algorithms with approximation factors of  $8$ ,  $\log_{\frac{8}{7}}(n) + 1$  and  $\ln(n)$  respectively. Third, we present distributed approaches to solve the problems, although we believe that in smaller WLANs (of the order of 100 APs) centralized algorithms are still feasible to execute. Note that distributed solutions are preferred in large networks, as centralized solutions will lead to more frequent changes in associations causing increased signaling traffic over the wireless links. Fourth, through simulations we study the performance of the proposed distributed and centralized solutions for the three objectives and compare them with the optimum solutions.

**Related Work:** In 802.11 networks user nodes often use signal strength as the key metric in selecting the AP. In [5, 11], new metrics were studied to select a unicast AP instead of signal strength. Packet error rate and number of users were used in [5]. The authors showed deployability and robustness of their AP selection architecture. Association time, system load, and signal/noise ratio (SNR) together were used to initiate handoff in [11]. The authors argued that their approach can provide Quality of Service (QoS) guarantee. However, these works did not consider load-balancing between APs. Recent work [1] has explored the idea of association control to balance the

---

\*This work is supported by the National Science Foundation under Grants CNS-0546630 (CAREER Award) and CNS-0403342.

network load and provided max-min fairness among users. The authors in [1] proved that balancing the network load is equivalent to achieving the max-min fairness, and presented algorithms that achieve a constant-factor approximation to max-min fair bandwidth allocation. However, they primarily focused on unicast traffic. For broadcast service in wireless Mesh networks, the optimal association algorithm was studied in [6], where minimum cost based greedy selection of an AP can decrease the size of the broadcast tree. The authors proposed the concept of multi-association, where the AP for unicast traffic and the AP for broadcast traffic are independently chosen by exploiting multiple coverages that are typical in mesh networks.

## 2 Preliminaries

### 2.1 Network Model

We consider a WLAN with a set of users  $U$  and a set of access points  $A$ . The maximum possible data rate on a link from an AP  $a$  to a user  $u$  is denoted by  $r_{a,u}$ . If an AP multicasts packets to the users associated with it, the AP uses the lowest rate among these users' maximum possible data rates on the links to this AP. We assume that MAC layer multicast/broadcast can support multi-rate transmission<sup>1</sup>. However, if the basic data rate is always used for multicast/broadcast, MNU, BLA and MLA problems are still NP-hard because our NP-hardness proofs for these problems do not require multi-rate transmission.

Each user node and each AP has a single radio. We assume that the radio channels of the neighboring APs are configured such that they do not interfere, which is reasonable since the newer IEEE 802.11a standard operates in the 5 GHz spectrum that supports 12 non-overlapping channels in US/Canada. The APs are connected using a wired LAN to one or more gateways that provide connectivity to the Internet. Each user may request one multicast stream from the WLAN. This is similar to our TV services where a user typically watches only one TV channel at any time. A user requesting a multicast (unicast) stream is referred to as a multicast (unicast) user. If a user can only be a unicast user or a multicast user, we do not need to do any other modification to the 802.11 standard except for that the association algorithm of 802.11 is replaced by our association algorithm for multicast users. If a user can be both a unicast as well as a multicast user, the network framework described in [6] can be applied, where the APs are synchronized through a time-synchronization protocol and each user independently selects one AP for unicast and another one for multicast services.

### 2.2 Objective Functions

**Definition 1 Multicast Load:** *the multicast load of an AP is the fraction of time that the AP is busy in transmitting multicast flows; the total multicast load of a network is the sum of all APs' multicast load in the network.*

**Maximizing the Number of Users (MNU):** When there is a heavy demand for multicast flows, all the user's requests can not be met. For such scenarios, we define the

<sup>1</sup>Recent research [4] has implemented the multi-rate broadcast/multicast.

goal to be maximization of the number of users that get multicast service from the network. Although the network revenue can be a function of both unicast and multicast flows, under typical network revenue models, the number of satisfied users will result in higher revenue. An example revenue model is when the unicast services have a monthly charge, but the multicast services are charged based on the time for which multicast streams are served to users. This is like the Pay-per-view service offered by most cable and satellite TV services today. Under such a model, increasing the number of satisfied multicast users will increase the total revenue for the service provider.

**Balancing the Load among APs (BLA):** In order to reduce the impact of multicast services on unicast flows, it is critical to reduce the size of the multicast period. This can be achieved by balancing the multicast load of the APs. More precisely, the objective here is to minimize the maximum multicast load among all APs. Consider a revenue model where one multicast flow is included in the basic monthly charges. Assume that the revenue function for unicast flows is convex, i.e., marginally decreasing with increasing bandwidth. Convex revenue functions are well known for achieving fairness among flows. Then balancing the multicast load will typically lead to fairness among the unicast flows and a higher total revenue, assuming uniform distribution of unicast users across the APs.

**Minimizing the Load of APs (MLA):** In order to free up the maximum amount of total time for unicast services, the total multicast load needs to be minimized. Although this can lead to uneven distribution of multicast load, for some revenue models this may be of interest. Consider a revenue model where one multicast flow is included in the basic monthly charges. However, the unicast services are charged per byte. In scenarios where there is a high demand for unicast traffic, maximizing the total amount of unicast traffic will maximize the revenue while satisfying the multicast users.

Note that solutions to the BLA and MLA problems will implicitly optimize maximum interference from an AP and total interference from all the APs, resulting due to multicast transmissions.

**An Example:** We use the example scenario shown in Figure 1 to describe these three problems. The WLAN consists of two APs,  $a_1, a_2$ , and, 5 users,  $u_1, u_2, \dots, u_5$ . The multicast sessions requested by each user and the data rates (in Mbps) between the users and the APs are indicated in the figure.

If the multicast data rates of  $s_1$  and  $s_2$  are both 3 Mbps, this WLAN can not support all the users for multicast because  $u_1$  and  $u_2$  can only be associated with  $a_1$ , and  $a_1$  can not provide multicast service to  $u_1$  and  $u_2$  simultaneously. If both  $u_1$  and  $u_2$  are supported by  $a_1$  then the total load on  $a_1$  will be  $\frac{3}{3} + \frac{3}{6} > 1$ , which is infeasible. In such scenarios, the objective of maximization of number of users (MNU) is relevant. One of the optimal solutions is that  $u_2, u_4$ , and  $u_5$  are associated with  $a_1$  and  $u_3$  is associated with  $a_2$ . This results in a load of  $\frac{3}{4}$  at AP  $a_1$  and a load of  $\frac{3}{5}$  at AP  $a_2$ .

Suppose the data rate of  $s_1$  and  $s_2$  are both 1 Mbps and the objective is to balance the multicast load among

APs (BLA) by minimizing the maximum multicast load among the APs. In the optimal solution  $u_1, u_2$ , and  $u_3$  are associated with  $a_1$ , and  $u_4$  and  $u_5$  are associated with  $a_2$ . The load of  $a_1$  will thus be  $\frac{1}{3} + \frac{1}{6} = \frac{1}{2}$  and the load of  $a_2$  will be  $\frac{1}{3}$ .

Suppose the data rate of  $s_1$  and  $s_2$  is 1 Mbps and the objective is to minimize the total load of all APs for multicast streams (MLA). In the optimal solution all users are associated with  $a_1$ , which results in a total AP load of  $\frac{1}{3} + \frac{1}{4} = \frac{7}{12}$ .

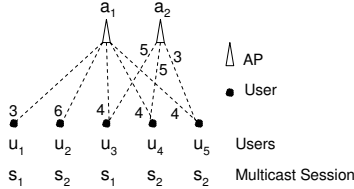


Figure 1. An example network scenario

### 3 Maximizing the Number of Users (MNU)

We show that MNU is an NP-hard problem, by showing a reduction from the Subset Sum problem, which is described in [3]. Because the Subset Sum problem is NP-hard, MNU problem is also NP-hard. Note that MNU is trivially in  $P$ , if there is only one multicast session in a WLAN. For a single session, all APs can choose to transmit at the lowest rate that does not violate the maximum multicast period.

#### 3.1 Centralized MNU

In order to solve this problem, we present a reduction from the MNU problem to the Maximum Coverage with Group Budgets (MCG)[2] problem.

**Definition 2 Maximum Coverage with Group Budgets (MCG) - cost version:** There are  $m$  subsets  $S_1, S_2, \dots, S_m$  of a ground set  $X$ . There are  $l$  sets  $G_1, G_2, \dots, G_l$ , each  $G_i$  being a subset of  $\{S_1, \dots, S_m\}$ . Each  $G_i$  is a group and the groups are disjoint from each other<sup>2</sup>. A cost  $c(S_j)$  is associated with each set  $S_j$ . Further, each group  $G_i$  is given a budget  $B_i$  and the overall budget is  $B$ . The objective is to find a subset  $H$  of  $\{S_1, \dots, S_m\}$  to maximize the size of the union of sets in  $H$  under the limitation that the total cost of the sets in  $H$  is at most  $B$ , and for any group  $G_i$ , the total cost of the sets in  $H \cap G_i$  is at most  $B_i$ .

**Theorem 1** MNU can be reduced to MCG problem.

**Proof:** The set of all users becomes the set  $X$  in the instance of MCG. Corresponding to each AP, we create  $m \times |S|$  subsets of  $X$  in MCG, where  $m$  is the number of discrete transmission rates that the WLAN supports and  $S$  is the set of multicast sessions. Thus, each subset corresponds to an AP, a single transmission rate, and a multicast session. The cost of a subset is the ratio of the corresponding multicast session's data rate and the transmission rate. All such subsets that are related to AP  $a_i$  form the group  $G_i$ . The budget  $B_i$  for the group  $G_i$  is the fraction of the

<sup>2</sup>If they are not disjoint from each other, we can make them disjoint by making copies of sets in  $S_1, \dots, S_m$ .

time AP  $a_i$  spends on multicast transmissions. For our problem, there is no overall budget limitation for the whole network, i.e.,  $B = \infty$ , as we assume that the capacity of the wired network is not the bottleneck.  $\square$

**Example – MNU:** If the data rate of  $s_1$  and  $s_2$  is 3 Mbps in the WLAN shown in Figure 1, we can reduce the MNU problem for the WLAN to the MCG problem shown in Figure 2. One of the optimal solutions for this MCG problem is  $H = \{S_4, S_5\}$ .

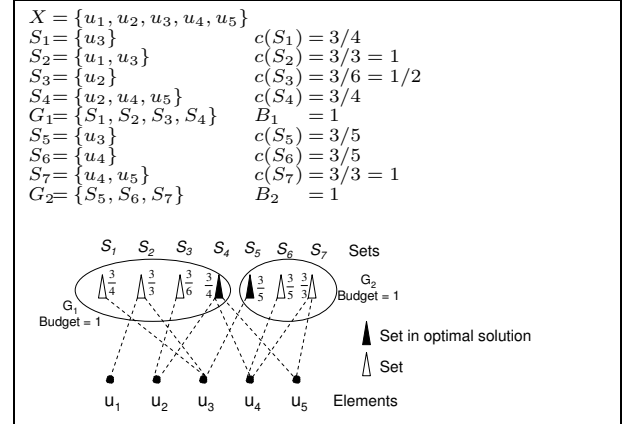


Figure 2. The reduction from MNU problem for the WLAN in Figure 1 to MCG problem

We use the above reduction to reduce any arbitrary instance of MNU to an instance of the MCG problem. In [2], the authors presented a greedy algorithm for MCG as it is an NP-hard problem. Because there is no overall budget limitation for our problem, we adapt the algorithm in [2] and present the modified algorithm below.

#### Algorithm Centralized MNU

1.  $H \leftarrow \phi, X' \leftarrow X$ .
2. **repeat**
3.    $flag \leftarrow 0$
4.   **for**  $i = 1, 2, \dots, n$  **do**
5.     **if**  $c(H \cap G_i) < B_i$  **then**
6.        $k \leftarrow \operatorname{argmax}_j \frac{|S_j \cap X'|}{c(S_j)}$  ( $S_j \in G_i$ )
7.        $A_i \leftarrow S_k$
8.        $flag \leftarrow 1$
9.     **else**  $A_i \leftarrow \phi$
10.   **endfor**
11.   **if**  $flag = 0$  **then Break**
12.    $r \leftarrow \operatorname{argmax}_i \frac{|A_i \cap X'|}{c(A_i)}$
13.    $H \leftarrow H \cup A_r, X' \leftarrow X' - A_r$
14.   **if**  $X' = \phi$  **then break**
15. **endrepeat**
16. **output**  $H$

Figure 3. Centralized solution for MNU

The algorithm greedily picks up subsets with minimum cost for every additional element until either all elements have been covered or until each group's budget has been violated by the last selected subset for the group. In the pseudo-code presented in Figure 3,  $H$  represents the set of selected subsets at any step. The set  $X'$  denotes the elements of  $X$  which have not yet been cover by the subsets

in  $H$ . The statements from line 3 to line 14 are repeatedly executed until all the group budgets are exceeded or all elements of  $X$  get covered. The variable *flag* is used for this purpose in line 11. In the *for* loop, *Centralized MNU* finds a set  $S_j$  in every group  $G_i$  whose budget has not been exceeded, and  $S_j$  is the set which is the most cost-effective set in the group  $G_i$ , i.e.,  $\frac{|S_j \cap X'|}{c(S_j)} = \max_{D \in G_i} \frac{|D \cap X'|}{c(D)}$ . Then in line 12, *Centralized MNU* finds the most cost-effective set in the sets selected in the *for* loop. This set is added into  $H$  and the elements in this set is removed from  $X'$  in line 13. Eventually, we get the output  $H$ .

Obviously,  $H$  does not obey the group budget requirements. We assume the cost of any single set  $S_j$  in any group  $G_i$  is not more than the budget of  $G_i$ . We partition  $H$  into two subsets  $H_1$  and  $H_2$ .  $H_2$  contains those sets  $S_j$  which when added to  $H$  caused the budget of some group  $G_i$  to be violated.  $H_1 = H - H_2$ . Observe that  $H_1$  and  $H_2$  by themselves do not violate the budget constraints and one of these two sets must be covering at least  $1/2$  the number of elements covered by  $H$ . Out of  $H_1$  and  $H_2$ , we select the one which covers the most number of elements. The final solution directly maps to the solution to the MNU problem.

**Theorem 2** *The algorithm Centralized MNU is an 8-approximation algorithm for MNU problem with no total budget limitation.*

**Proof:** Define  $X(H)$  as the number of the elements covered by the subsets of  $X$  in  $H$ . Let OPT be some fixed optimal solution to the given problem instance. In [2], it was proved that  $X(H) \geq \frac{1}{4}X(OPT)$ . As either  $H_1$  or  $H_2$  must contain at least half the elements covered by  $H$ , *Centralized MNU* is an 8-approximation algorithm for MNU problem.  $\square$

**Example – Centralized MNU:** We run *Centralized MNU* algorithm on the MCG problem shown in Figure 2.  $S_4$  is selected in the first round because it has the maximum value of  $\frac{|S_4 \cap X'|}{c(S_4)} = \frac{3}{4} = 4$  among all  $S_i$  ( $1 \leq i \leq 7$ ). After that,  $H = \{S_4\}$ ,  $X' = \{u_1, u_3\}$ . In the second round,  $S_2$  is selected because it has the maximum value of  $\frac{|S_2 \cap X'|}{c(S_2)} = \frac{2}{1} = 2$  and  $c(H \cap G_1) = c(S_4) = 3/4 < B_1 = 1$ . After that, we get output  $H = \{S_2, S_4\}$  because  $X' = \phi$ . Now,  $c(H \cap G_1) = c(S_2) + c(S_4) = 7/4 > B_1 = 1$ . We divide  $H$  into  $H_1 = \{S_4\}$  and  $H_2 = \{S_2\}$ . Eventually, we get output  $H_1$  because  $H_1$  cover more elements than  $H_2$ . Therefore,  $u_2, u_4, u_5$  are associated with  $a_1$  and 3 users get multicast streams. If we use strongest signal based approach,  $u_1, u_2, u_5$  can only be associated with  $a_1$  and  $u_3, u_4$  can only be associated with  $a_2$ . If  $u_1, u_3$  are associated with APs first,  $u_2, u_4, u_5$  can not be associated with APs because of the load limitation of APs. So, only 2 users get multicast service.

### 3.2 Distributed MNU

We provide a simple distributed algorithm to maximize the number of users. Intuitively, because the total resource of the network (APs) for multicast is fixed, every user should increase the total load minimally in order to attempt increasing the total number of users. Due to lack of global

view, the distributed approach has to take decisions based only on local information obtained from the APs.

A user periodically sends a query message to each of its neighboring APs. Then, each AP responds with a message containing information about the current multicast sessions being transmitted and the data rate of such transmissions. The user also knows the maximum data rate for the link between itself and its neighboring APs. If a user is currently associated with some AP  $a$ , this user also needs to know the load of  $a$  if it leaves AP  $a$ . According to the information from the neighboring APs, the user calculates the total load of its neighboring APs if it can associate with it without violating the maximum multicast load for that AP. The user then associates with the neighboring AP that results in minimum increase in total load. If there are several APs that result in the same minimum increase in total load, the user can associate with the one with the strongest signal.

**Example – Distributed MNU:** Consider that the data rate of  $s_1$  and  $s_2$  is 3 Mbps in the WLAN in Figure 1, and users use the distributed algorithm in the order  $u_1, u_2, u_3, u_4, u_5$ . First  $u_1$  associates with  $a_1$ . Then,  $u_2$  can not associate with  $a_1$  because of the load limitation of  $a_1$ . After that,  $u_3$  associates with  $a_1$ , which results in the minimum total load 1 of  $u_3$ 's neighboring APs  $a_1, a_2$ . Similarly,  $u_4, u_5$  are associated with  $a_2$ . Eventually, 4 out of the 5 users receive their multicast service.

**Lemma 1** *The algorithm Distributed MNU converges when the network becomes static if the users in an AP's transmission range make their local decisions one by one.*

**Proof:** Because the users in an AP's transmission range make decision one by one, each user always operates on the most up-to-date information about the multicast sessions. First, we consider the scenario where there are no new users joining the network. If a user has been associated with an AP and wants to change its association, it should reduce the total load of all of its neighboring APs, which also means the total load of the whole network will be reduced. As the number of discrete levels of data rates, number of APs, and number of users are limited, the total load of the whole network should be eventually reduced to a final value in finite steps. If a new user joins the network, the total load of the whole network also should reach a final value in limited steps. The network is static, and the total number of users is finite. The number of new users joining the network is also finite. Therefore, the distributed algorithm converges for a static network if the users make decision one by one.  $\square$

However, if the users in an AP's transmission range make their local decisions simultaneously, the algorithm *Distributed MNU* may not converge. The example scenario is shown in [3].

## 4 Balancing the Load among APs (BLA)

We present a reduction from Minimum Makespan Scheduling problem [10] to the BLA problem, which is described in [3], to prove the NP-hardness of BLA. Based on the reduction, BLA is NP-hard because the minimum makespan scheduling problem is NP-hard. Note that BLA is a P problem if there is only one multicast session. As

there are constant number of discrete transmission rates, each of these transmission rates can be checked in sequence for feasibility of being the maximum transmission rate. For a given value of the transmission rate, all APs are assigned the same rate (as the optimization function only concerns the maximum). Among all the transmission rates the highest rate (when assigned to all APs) that provides service to all users, is the solution.

#### 4.1 Centralized BLA

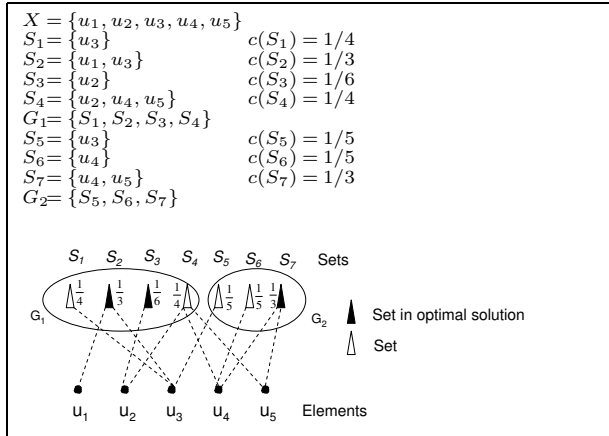
In order to solve the BLA problem, we present a reduction to the Set Cover with Group Budgets (SCG) [2] problem.

**Definition 3 Set Cover with Group Budgets (SCG):** There is a set  $S = \{S_1, S_2, \dots, S_m\}$  of subsets of a ground set  $X$ . The set  $S$  is partitioned into groups  $G_1, G_2, \dots, G_l$ . A cost  $c(S_j)$  is associated with each set  $S_j$ . The objective is to find a subset  $H$  of  $S$  such that all elements of  $X$  are covered by sets in  $H$  and  $\max_{i=1}^l c(H \cap G_i)$  is minimized.

**Theorem 3** The problem of balancing load among APs (BLA) can be reduced to SCG problem.

**Proof:** The reduction from BLA to SCG is similar to the reduction from MNU to MCG in section 3. We denote the set of all users as  $X$ . For each AP, we create multiple subsets, each corresponding to a particular combination of session number and transmission rate. The cost of each subset is obtained by dividing the rate of the corresponding session by the transmission rate associated with that subset. All of the subsets that are related to AP  $a_i$  form the group  $G_i$ .  $\square$

**Example – BLA:** If the data rate of  $s_1$  and  $s_2$  is 1 Mbps in the WLAN in Figure 1, we can reduce the BLA problem for the WLAN to the SCG problem shown in Figure 4. The optimal solution of this SCG problem is  $H = \{S_2, S_3, S_7\}$ .



**Figure 4. The reduction from BLA problem for the WLAN in Figure 1 to SCG problem**

SCG problem is also NP-hard. In [2], the authors gave an algorithm for the cardinality version of SCG based on the greedy algorithm for MCG. Our algorithm is similar. The algorithm is shown in Figure 5. Assume the number of the elements in the ground set  $X$  is  $n$ .

#### Algorithm Centralized BLA

1. Guess the optimal value  $B^*$  and assume there is an optimal cover  $H^*$  such that  $\max_{i=1}^l c(H^* \cap G_i) \leq B^*$
2. Create an instance of MCG by having a budget of  $B^*$  on each group  $G_i$ . Run *Centralized MNU*, which covers at least  $\frac{1}{8}$ th the elements in  $X$ . Remove the covered elements from  $X$  and all subsets of  $X$ , and run *Centralized MNU* again. Iterating *Centralized MNU*  $\log_{8/7} n + 1$  times results in a solution that covers all elements. Let  $H = \{\text{all sets } S_i \text{ added when repeating Centralized MNU}\}$ .
3. Output  $H$ .

**Figure 5. Algorithm centralized BLA**

**Theorem 4** The algorithm *Centralized BLA* is an  $(\log_{8/7} n + 1)$ -approximation algorithm for BLA problem.

**Proof:** In each iteration of running *Centralized MNU*, the total cost of the sets added from any group  $G_i$  is bounded by  $B^*$ . Because we iterate *Centralized MNU*  $\log_{8/7} n + 1$  times in algorithm *Centralized BLA*, the total cost of the sets added from any group  $G_i$  is bounded by  $(\log_{8/7} n + 1)B^*$  when all elements in  $X$  are covered. Therefore, *Centralized BLA* is an  $(\log_{8/7} n + 1)$ -approximation algorithm for BLA.  $\square$

To implement the algorithm *Centralized BLA*, there is an issue of how to guess  $B^*$ . Let the maximum cost among all subsets of  $X$  in all groups be  $c_{max}$ .  $B^*$  also should be less than 1. Therefore, we can try several (a constant number) values of  $B^*$  between  $c_{max}$  and 1 to get the best result.

**Example – Centralized BLA:** We run *Centralized BLA* algorithm on the SCG problem shown in Figure 4. Let  $B^* = 1/2$  and create an instance of MCG problem. Then run *CentralizedMNU*, and get the output  $\{S_4\}$ . After that, remove  $u_2, u_4, u_5$  from every  $S_i$  ( $1 \leq i \leq 7$ ) and create a new instance of MCG problem. Run *CentralizedMNU* again, and get output  $\{S_2\}$ . Therefore, all users are associated with  $a_1$ .

#### 4.2 Distributed BLA

As the objective is to balance the load among APs, a user should attempt to minimize the maximum load of the neighboring APs. The following is the distributed algorithm for BLA.

A user periodically sends a query message to each of its neighboring APs. Then, each AP responds with a message containing information about the multicast sessions that this AP supports and the rates for the supported multicast sessions. The user also knows the maximum data rate for the link between itself and its neighboring APs. If a user is currently associated with some AP  $a$ , this user also needs to know the load of  $a$  if it leaves AP  $a$ . According to the information from the neighboring APs, the user calculates the new load of a neighboring AP if it is associated with this AP. For each AP it computes the new vector of loads of neighboring APs if it decides to join that AP. Each load vector is sorted in non-increasing order of the loads of APs in that vector. The user then determines to receive the desired flow from the AP that locally minimizes the sorted new load vector. (We define two sequences with non-increasing order to be equal if each pair of values at the same position of these two sequences are equal. If two

sequences are not equal, we compare the first pair of unequal elements at the same position and the sequence with the smaller element is smaller than the other sequence.)

**Example – Distributed BLA:** Assume that the data rates of  $s_1$  and  $s_2$  are both 1 *Mbps* in the WLAN in Figure 1, and users run the distributed algorithm in the order  $u_1, u_2, u_3, u_4, u_5$ . First  $u_1, u_2$  is associated with  $a_1$ . After that,  $u_3$  makes the decision. If  $u_3$  is associated with  $a_1$ , it's neighboring APs' load vector in non-increasing order is  $(1/2, 0)$ ; if  $u_3$  is associated with  $a_2$ , the load vector is  $(1/2, 1/5)$ . Therefore,  $u_3$  is associated with  $a_1$ . Next, if  $u_4$  is associated with  $a_1$ , its neighboring APs' load vector with non-increasing order is  $(7/12, 0)$ ; if  $u_4$  is associated with  $a_2$ , the load vector is  $(1/2, 1/5)$ . Hence,  $u_4$  is associated with  $a_2$ . Similarly,  $u_5$  is associated with  $a_2$ . Eventually, the load of  $a_1$  is  $1/2$  and the load of  $a_2$  is  $1/3$ , which is also the optimal solution.

**Lemma 2** *The distributed algorithm for BLA converges when the network is static if the users in an AP's transmission range make decision one by one.*

**Proof:** The proof is similar to the proof of Lemma 1. If a user has been associated with an AP and wants to change its association, it should reduce the vector of neighboring APs' loads, which also means the global vector of all APs' loads in the network is reduced. Because the number of different data rates, the number of APs, and the number of users are all finite, the vector of all APs' loads in the network will eventually settle down to a final value in limited number of steps. If there is a new user who joins the network, the sequence of all APs' loads in the network also should reach a final value in limited steps. Therefore, the distributed algorithm converges when the network is static if the users in an AP's transmission range make decision one by one.  $\square$

However, if the users in an AP's transmission range make their local decisions simultaneously, the distributed algorithm for BLA may not converge. The example scenario is same as the scenario for the distributed algorithm for MNU shown in [3].

## 5 Minimizing the Load of APs (MLA)

We show that MLA is an NP-hard problem, by showing a reduction from the Set Cover problem, which is described in [3]. MLA is NP-hard as set cover problem is NP-hard.

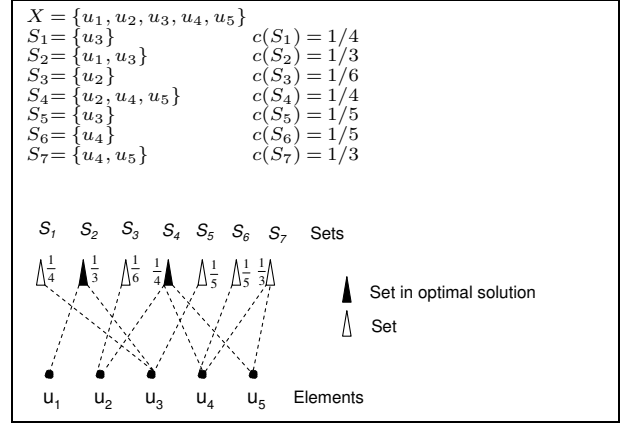
### 5.1 Centralized MLA

In order to solve the MLA problem, we reduce it to the Set Cover problem.

**Theorem 5** *The problem of minimizing the load of APs (MLA) can be reduced to set cover problem.*

**Proof:** We regard the set of all of the users as the ground set  $X$ . The construction is same as the construction in the proof of Theorem 3 except that there are no groups since we are only concerned the total multicast load of a network, not each AP's load for MLA problem.  $\square$

**Example – MLA:** If the data rate of  $s_1$  and  $s_2$  are 1 *Mbps* in the WLAN in Figure 1, we can reduce the MLA problem for the WLAN to the set cover problem shown in



**Figure 6. Reducing MLA problem for the WLAN in Figure 1 to the set cover problem**

Figure 6. The optimal solution of this set cover problem is  $H = \{S_2, S_4\}$ .

The greedy algorithm for set cover is well known. The cost version of greedy set cover algorithm is described in [10], which can be directly used to solve MLA problem after reducing it to an instance of the set cover problem.

**Example – Centralized MLA:** We run *CostSC* algorithm on the set cover problem corresponding to Figure 6.  $S_4$  is selected in the first round because it has the maximum value of  $\frac{|S_4 \cap X'|}{c(S_4)} = \frac{3}{1/4} = 12$  among all  $S_i$  ( $1 \leq i \leq 7$ ). After that,  $H = \{S_4\}$ ,  $X' = \{u_1, u_3\}$ . In the second round,  $S_2$  is selected because it has the maximum value of  $\frac{|S_2 \cap X'|}{c(S_2)} = \frac{2}{1/3} = 6$ . After that, we get output  $H = \{S_2, S_4\}$  because  $X' = \phi$ . Therefore, all users are associated with AP  $a_1$ , which is also the optimal solution.

The following theorem's proof is given in [10].

**Theorem 6** *The algorithm CostSC is an  $(\ln n + 1)$ -approximation algorithm for set cover problem.*

### 5.2 Distributed MLA

Because the objective of MLA is to minimize the total load of the APs in the network, intuitively, a user should be associated with the AP which increases the total load minimally. Therefore, we use the same distributed algorithm for MLA as the one for MNU.

**Example – Distributed MLA:** Consider that the data rate of  $s_1$  and  $s_2$  is 1 *Mbps* in the WLAN in Figure 1, and users use the distributed algorithm in the order  $u_1, u_2, u_3, u_4, u_5$ . First  $u_1, u_2$  is associated with  $a_1$ . After that,  $u_3$  is associated with  $a_1$  because the total load of  $u_3$ 's neighboring APs  $a_1$  and  $a_2$  is  $\frac{1}{3} + \frac{1}{6} = \frac{1}{2}$  if  $u_3$  is associated with  $a_1$  and the total load is  $\frac{1}{3} + \frac{1}{6} + \frac{1}{5} = \frac{7}{10}$  if  $u_3$  is associated with  $a_2$ . Similarly,  $u_4, u_5$  are associated with  $a_1$ . Eventually, all users are associated with AP  $a_1$ , which is also the optimal solution.

## 6 Performance Evaluation

In this section we report on performance studies of the proposed association algorithms for multicast using simulations in the Network Simulator ns2 [8]. The simulation source code can be downloaded from

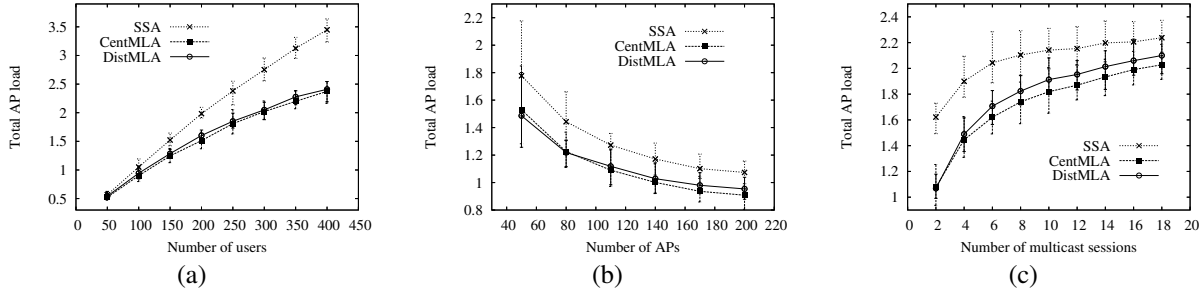


Figure 7. Total AP load for multicast sessions

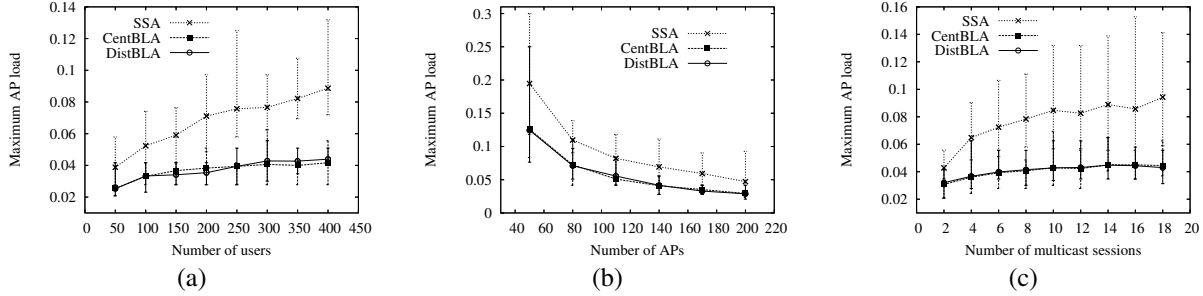


Figure 8. Maximum load among APs for multicast sessions

<http://www.cse.ohio-state.edu/~chenai/ICDCS07/>. The simulation results show the average performance of our algorithms, while our analysis in the previous sections only shows the performance of our algorithms in the worst cases. We compare the performance of the three algorithms, MLA, BLA, and MNU, with the signal strength based association algorithm (SSA), which always lets a user associate with the AP providing the strongest signal among all the neighbor APs of this user. We have simulated the proposed algorithms over  $1.2km^2$  area with up to 200 APs and 400 users randomly located in the area. The radio propagation range of both AP and user is 200m. The transmission rates and their distance thresholds are adopted from [7]. The users collect information of neighbor APs using active scanning [9]. Every user joins one multicast session. The APs operate in IEEE 802.11a infrastructure mode. We use 0.9 as the load limitation of multicast for every AP. Unless otherwise specified, we use 5 multicast sessions. Each user selects one of the multicast sessions at random. These simulation settings are used for all algorithms unless mentioned otherwise. We depict the average, min and max values for 40 random scenarios in the figures.

**Minimize Load of APs:** Figure 7 shows the total load with respect to the number of users, APs, and sessions, respectively. Figure 7(a) varies the number of users for 200 APs, Figure 7(b) changes the number of APs with 100 users, and Figure 7(c) changes the number of session with 200 APs and 200 users. Figures 7(a) and 7(c) show that the total AP load increases, as the number of users and the number of sessions increase because of increased multicast demand. The total AP load, however, has an inverse relationship to the number of APs as shown Figure 7(b). The reason is that the resulting increased density of APs allows for higher transmission rate between APs and users. We can observe that the centralized and distributed MLA

algorithms perform better than SSA through simulations in Figure 7. The total multicast load of the centralized MLA and the distributed MLA perform 31.1% and 30.1% better than that of SSA at 400 users, respectively in Figure 7(a). The distributed algorithm performs only slightly worse (up to 5%) than the centralized algorithm.

**Balance Load among APs:** Figure 8 shows the maximum load among APs with respect to the number of users, APs, and sessions, respectively. Figure 8(a) varies the number of users for 200 APs, Figure 8(b) changes the number of APs with 100 users, and Figure 8(c) changes the number of session with 200 APs and 200 users. The centralized and distributed BLA algorithms have up to 52.9% and 50.5% lower maximum load than SSA at 400 users, respectively (Figure 8 (a)). Moreover, unlike the SSA algorithm, for the distributed and centralized BLA algorithms, the maximum load increases slowly with the number of users or sessions (Figures 8 (a) and 8 (c)). Figure 8 (b) shows that the maximum load decreases as the number of APs increases, since the multicast load can be shared by more APs. We observe that the centralized and distributed BLA algorithms have similar performance.

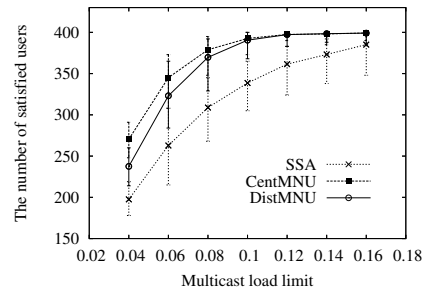


Figure 9. The number of satisfied users

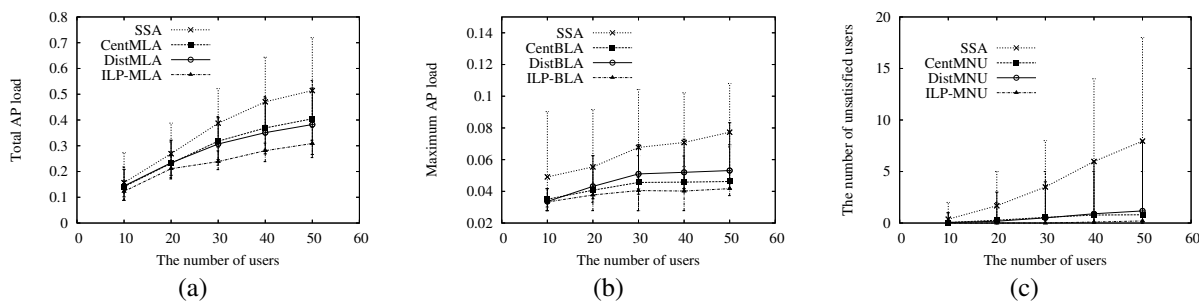


Figure 10. The optimal solution of MLA, BLA, and MNU problems

**Maximize Number of Users:** Figure 9 shows the number of satisfied users with respect to the multicast load limitation with 400 users, 100 APs, and 18 multicast sessions. We define the multicast load in Definition 1. As the multicast load limitation increases, the number of satisfied user increases as well. The satisfied number of users of the centralized and distributed MNU algorithms are 36.9% and 20.2% higher than that of SSA at the load limitation 0.04.

**Optimal Solutions:** In Figure 10, we evaluate the optimality of MLA, BLA, and MNU algorithms with respect to the number of users. Because there has been no other research work considering the problems mentioned in this paper, we have implemented ILPs for MLA, BLA, and MNU problems based on the ILP of set cover problem to compute the optimal solutions. Note that MLA, BLA, and MNU are NP-hard problems. As ILP takes exponential time to arrive at solutions, we limit our evaluation to small networks. 30 APs are randomly located in  $600m^2$  area. In Figure 10(c), the multicast load limitation of every AP is 0.042. The total AP loads of the centralized and distributed MLA algorithms are 25% and 22.2% higher than the one of the optimal solution at 30 users in Figure 10 (a). The maximum loads among APs of the centralized and distributed BLA algorithms are 12% and 22.6% higher than the one of the optimal solution at 40 users in Figure 10 (b). Although on average the MNU algorithm performs much closer to the optimal algorithm than the SSA algorithm, the maximum number of unsatisfied users for the centralized and distributed MNU algorithms are 5 and 8 respectively (Figure 12(c), 50 users<sup>3</sup>) but for the optimal solution it is 1. If networks are small, it is possible in some scenarios for the distributed algorithms to perform even better than the centralized algorithms (Figure 12(a)). The reason is that in small networks, the distributed algorithms have relatively more global information than in case of large networks.

## 7 Conclusion

Motivated by recent reports of dense deployments of APs in WLANs, we study techniques for exploiting overlapping coverage from neighboring APs to optimize performance of multicast services. Three objective functions based on different revenue functions and network scenarios are studied: maximizing the number of users (MNU), balancing the load among APs (BLA) and minimizing the

load of APs (MLA). We show that these problems are NP-hard. We present centralized approximation algorithms and distributed algorithms for these problems. Using simulations we evaluate the performance of these protocols and find that compared with multicasting from associated APs chosen based on strongest signal, the number of users can be increased by up to 36.9%, and the maximum AP load and the total load can be reduced by up to 52.9% and 31.1%, respectively. We conclude that the impact of multicast services on unicast services in WLANs can be effectively reduced by association control mechanisms.

As part of future work, we will explore local coordination mechanisms to guarantee optimization of the global objectives, and extend our solutions to explicitly consider interference from neighboring nodes.

## References

- [1] Y. Bejerano, S.-J. Han, and L. Li, "Fairness and Load Balancing in Wireless LANs Using Association Control," in *Proc. of Mobicom*, Sept. 2004.
- [2] C. Chekuri and A. Kumar, "Maximum Coverage Problem with Group Budget Constraints and Applications," in *Proc. of the APPROX*, 2004.
- [3] A. Chen, D. Lee, and P. Sinha, "Optimizing Multicast Performance in Large-Scale WLANs," in *Technical Report OSU-CISRC-3/07-TR21*, Dept. of Computer Science and Engineering, The Ohio State University, March 2007.
- [4] C. T. Chou and A. Misra, "Low Latency Multimedia Broadcast in Multi-rate Wireless Meshes," in *Proc. of the 1st IEEE Workshop on Wireless Mesh Networks*, 2005.
- [5] Y. Fukuda, T. Abe, and Y. Oie, "Decentralized access point selection architecture for wireless LANs," in *Proc. of Wireless Telecommunications Symposium*, May 2004.
- [6] D. Lee, G. Chandrasekaran, and P. Sinha, "Optimizing broadcast load in Mesh Networks using Dual-Association," in *Proc. of the 1st IEEE Workshop on Wireless Mesh Networks*, 2005.
- [7] M. H. Manshaei and T. Turletti, "Simulation-Based Performance Analysis of 802.11a Wireless LAN," in *Proc. of International Symposium of Telecommunications (IST)*, 2003.
- [8] ns2: Network Simulator, "http://www.isi.edu/nsnam/ns/".
- [9] I. Ramani and S. Savage, "SyncScan: Practical fast handoff for 802.11 infrastructure networks," in *Proc. of the IEEE Infocom Conference*, Miami, FL, USA, March 2005.
- [10] V. Vazirani, *Approximation Algorithms*, Springer Verlag, 2001.
- [11] L. Wang, Z. Niu, Y. Zhu, H. Deng, and M. Yano, "Integration of SNR, load and time in handoff initiation for wireless LAN," in *Proc. of PIMRC*, September 2003.

<sup>3</sup>These details are not visible in the graph due to overlapping error bars