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Minimal Smart Access-Point Selection for Maximal Throughput in Wireless Mesh Networks

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Abstract —**The architecture and design optimization issues of the *Wireless Internet-access Mesh NETwork (WIMNET)* has been studied to provide a scalable wireless Internet access network. WIMNET may utilize two types of APs as wireless mesh routers to achieve the scalability with sufficient bandwidth while reducing costs. One is an expensive, programmable *smart AP (SAP)* that can use plural channels for wireless communications and has various functions for the Internet access. Another is an inexpensive, non-programmable *conventional AP (CAP)* that can use only one channel. To enhance the performance of WIMNET with a small number of costly SAPs, we have previously proposed the *SAP selection algorithm* of selecting a fixed number of SAPs from a given set of allocated APs. The simulation result observed the existence of a *minimal SAP set* providing the maximal throughput. In this paper, we propose the extension of this algorithm to finding the minimal SAP set with the maximal throughput. We verify the effectiveness of our proposal through simulations in four instances using the WIMNET simulator.**

Keywords: Wireless mesh network, smart access point, allocation, algorithm, communication route

1 Introduction

As an inexpensive and flexible access network to the Internet, the *wireless local area network (WLAN)* has been extensively deployed around the world. Because the WLAN does not need a wired cable to connect a host with an access point (AP), it has several advantages such as low installation and management costs, easy host relocations, and flexible service areas. An AP acts as a connection hub to a wired network in the WLAN. As a result, the WLAN has been installed at many places and organizations including governments, companies, homes, and schools. Nowadays, the WLAN service has become available even in moving public spaces such as trains and airplanes.

The WLAN, however, has a drawback such that one AP can cover only the limited area within approximately $100m$ distance due to the weak transmission signal. For the WLAN service to the wide area, multiple APs should be installed. These APs are usually connected through wired cables, whereas the cabling cost may impair the cost advantage of the WLAN. Besides, the cable may not be able to be laid down in places such as outdoors and old buildings. One solution to this problem is the mesh allocation of multiple APs using wireless communications between adjacent APs in the service area, in addition to conventional wireless communications between APs and hosts. Distant APs can be communicated through multihop communications, where intermediate APs act as repeaters to reply packets. This multihop WLAN is called the *wireless mesh network* [1].

Among several variations under studies for the wireless mesh network, we have focused on the one that uses only APs as wireless mesh routers and realizes communications between APs mainly on the MAC layer with the *wireless distribution system (WDS)*. At least one AP acts as a *gateway (GW)* to the Internet, and any host can connect to the Internet through this GW. We have called it *WIMNET (Wireless Internet-access Mesh NETwork)* for convenience [2][3].

When the size of WIMNET is expanded for the increasing number of APs and hosts, it may meet two serious problems. One is the *increase of communication delay* due to the bandwidth shortage at the wireless links around the GW, because increasing traffics between the Internet and WIMNET must pass through them, whereas their bandwidth is limited. Another is the *degradation of dependability and communication quality* due to the increasing interference between wireless links. As a result, the number of APs in a single WDS must be limited to avoid the unacceptable interference.

In order to solve these problems, we have proposed the hierarchical structure for WIMNET that is composed of two types of APs and *WDS clusters*. As shown in Fig. 1, one WDS cluster consists of one expensive, programmable *smart AP (SAP)* as the cluster head, and plural inexpensive, non-programmable *conventional APs (CAPs)*. A SAP can use plural channels for wireless communications by equipped with additional network interface cards (NICs), and has various functions for the Internet access [4]. A CAP can use only one channel. The number of CAPs in one WDS cluster is limited because they need to periodically exchange the routing informa-

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tion for WDS. The WDS clusters are connected through SAPs using plural channels because their traffics are usually larger than those inside the WDS cluster. Then, the proper SAP selection among allocated APs [2] becomes very important because it determines the performance and the cost of WIMNET.

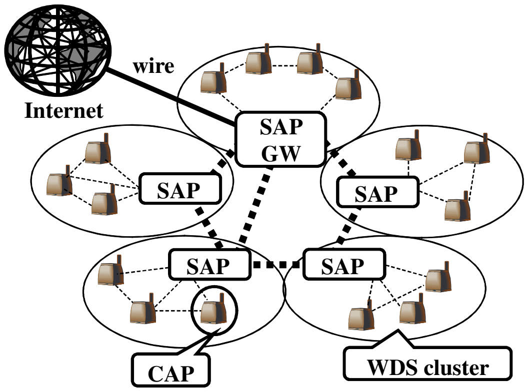

Figure 1: Outline of WIMNET

To solve this problem, we have previously proposed the *SAP selection algorithm* to select the fixed number of SAPs from a given set of allocated APs that maximizes the throughput [5]. This throughput maximization is sought by checking each feasible set of SAPs among APs that minimizes the maximum delay at one channel. This delay is estimated through the summation of the traffics among the interfered links using the same channel. The simulation results using the WIMNET simulator observed the existence of a *minimal SAP set* providing the maximal throughput.

In this paper, we propose the extension of the SAP selection algorithm to find this minimal SAP set with the maximal throughput. In this extension, we adopt the cost function in the SAP selection algorithm to check the maximality of the throughput. We verify the effectiveness of our proposal through simulations in four instances, where any result indicates that the SAP set by our algorithm provides the maximal throughput similar to the one where every AP becomes a SAP. We conclude that using our proposal, a large-size, high-performance WIMNET can be configured with a small number of expensive SAPs.

The rest of this paper is organized as follows: Section 2 reviews our previous works of the SAP selection algorithm for WIMNET. Section 3 presents the algorithm extension. Section 4 shows its evaluation results by simulations. Section 5 concludes the paper with some future works.

2 Previous Works of SAP Selection Algorithm

2.1 Formulation of SAP Selection Problem

As the inputs to the SAP selection problem, we assume that the AP network topology, the GW, the expected maximum number of associated hosts with each AP as traffic loads, the interference among the links, the transmission speed of each link, the WDS cluster size limit, and the channel interference matrix are given. As the output, the SAP set with the routing tree and NIC/channel assignments is requested such that they can minimize the maximum delay as the cost function. Then, the SAP selection problem can be formulated as follows:

A. Input:

- the AP network topology: $G = (V, E)$
  - the set of APs: V
  - the number of APs: $N = |V|$
  - the set of links between APs: E
  - the interference among links: $D = [d_{ijpq}]$, where $d_{ijpq} = 1$ if two links, $AP_i \rightarrow AP_j$ and $AP_p \rightarrow AP_q$, are interfered with each other, and $d_{ijpq} = 0$ otherwise
  - the bandwidth of $link_{ij}$: s_{ij} (Mbps)
  - the maximum expected number of associated hosts with AP_i: h_i
  - the Internet gateway: g ($\in$ V)
- the number of SAPs: M
- the WDS cluster size (the maximum number of CAPs in one WDS cluster): S
- the number of channels: P
- the channel interference matrix: $C = [c(i, j)]$
- the maximum number of NICs per SAP: Q

B. Output: the SAP set with the routing tree and NIC/channel assignments

C. Constraints: The following three conditions must be satisfied in the feasible solution:

(1) The gateway must be a SAP.

(2) Any CAP must not exist along the routing path between the GW and any SAP.

(3) Any CAP must have at least one connectable SAP as the cluster head.

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The *connectable SAP* represents a SAP that exists along the shortest path between the CAP and the GW, or exists within four hops from the CAP. The latter condition is necessary to increase the number of cluster head candidates for CAPs to obtain feasible solutions.

D. Objective: The cost function E representing the maximum delay should be minimized:

$$E = \max_{(i,j)} \left[t_{ij} + t_{ji} + \sum_{\substack{p=1 \\ d_{ijpq}=1 \vee d_{jipq}=1}}^{N} \sum_{q=1}^{N} t_{pq} c\left(y_{ij}, y_{pq}\right) \right] \quad (1)$$

where t_{ij} represents the traffic along the link from $AP_i \rightarrow AP_j$, and y_{ij} represents its assigned channel.

2.2 SAP Selection Algorithm

The SAP selection algorithm finds the SAP set minimizing E by applying the routing tree and NIC/channel assignment algorithms in [6] to each feasible SAP set in the given AP network. Here, to reduce the computation time, this algorithm discards the undesirable SAP sets by adopting the *maximum estimated SAP load* before applying routing/assignment algorithms. The following procedure describes the details of the SAP selection algorithm:

(1) Calculate the lower bound N_{LB}^{SAP} on the number of SAPs, which is equal to the number of WDS clusters. If the input number of SAPs M is smaller than it, set $M = N_{LB}^{SAP} = \lceil \frac{N}{W} \rceil$.

(2) Generate a new SAP set by selecting M APs for SAPs among N APs.

(3) Check the feasibility of the SAP set in (2) by satisfying the three constraints. If it is not feasible, go to (8).

(4) Calculate the *maximum estimated SAP load* in Sect. 2.3. If it is larger than the threshold there, go to (8).

(5) Apply the routing tree and NIC/channel assignment algorithms in [6]. If no feasible solution is obtained, go to (8).

(6) Calculate the cost function E.

(7) Update the best-found solution if E in (6) is smaller than the best one.

(8) Terminate the procedure if every SAP set is generated in (2). Otherwise, go to (2).

2.3 Maximum Estimated SAP Load

As the number of APs increases, the number of feasible SAP sets increases exponentially. Then, the computation time becomes unacceptably long, where the routing tree and NIC/channel assignment algorithms requires the inhibitory long time. To avoid this situation, the *maximum estimated SAP load* is calculated for each SAP set before their applications, and if the value is larger than the threshold, it is discarded because traffics are concentrated into a specific SAP that may become the bottleneck of WIMNET.

2.3.1 SAP Selection Weight by Hop Count

As the cluster head to a CAP, a SAP with the smaller hop count (number of hops) has the larger possibility than a SAP with the larger hop count due to the delay. Thus, the *SAP selection weight* by hop count is calculated for any pair of a SAP and a CAP to represent the possibility of belonging to the same cluster by $W_k = 1/2^k$.

2.3.2 Procedure for Maximum Estimated SAP Load

For each SAP in a SAP selection, the *maximum estimated SAP load* is calculated by the following procedure:

(1) Find the connectable SAPs in the SAP set for each CAP.

(2) Calculate the weighted average of the *SAP selection weights* among the connectable SAPs for each CAP.

(3) Multiply the maximum expected number of associated hosts h_i to this weighted average for each SAP.

(4) For each SAP, sum up the values of $W_k in$ of all the CAPs that can select this SAP as the cluster head, which becomes the *estimated SAP load*.

(5) Select the maximum value of (4) among all the SAPs in the SAP set for the *maximum estimated SAP load*.

2.3.3 Example of Estimated SAP Load

Figure 2 illustrates an example of calculating the *estimated SAP load* for CAP-A. The three SAPs $\{1, 2, 3\}$ are connectable for CAP-A. Because the hop count from CAP-A is three, two, and three to each SAP, the corresponding *SAP selection weights* are given by: $1/2^3$, $1/2^2$, $1/2^3$. Because h_i for CAP-A is 10, the estimated load for each of the three SAPs by CAP-A is 2.5, 5, and 2.5 as shown in Fig. 2. Then, after calculating them for every CAP, the *estimated SAP load* is calculated by summing up them for each SAP.

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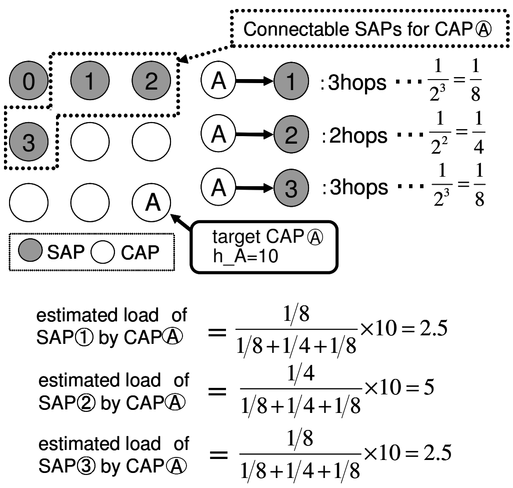

Figure 2: Example of estimated SAP load calculation.

2.3.4 Threshold for Traffic Concentration

The *maximum estimated SAP load* is compared with the given threshold Th to judge whether the SAP selection may cause the traffic concentration into a specific SAP or not. If it exceeds the threshold, the SAP selection is discarded. For this threshold, the twice of the average SAP load is used:

$$Th = \left(\frac{\sum_{i=1}^{N} h_i}{M} \right) \times 2. \qquad (2)$$

3 Extension of SAP Selection Algorithm

In this section, we propose the extension of the SAP selection algorithm to find a minimal SAP set that provides the maximal throughput for WIMNET. The idea in this extension is simple. Our previous simulation results in [5] observed that the SAP set minimizing the cost function E provides the maximum throughput among possible SAP sets when the number of SAPs is fixed. Thus, if we find the SAP set giving the minimal value of this cost function by applying the SAP selection algorithm while increasing the number of SAPs starting from its lower bound, it can be a minimal SAP set with the maximal throughput. In this paper, the minimality of the cost function is determined by the sufficient decrease of the change of the cost functions between two consecutive numbers of SAPs. Actually, the minimality is determined when the ratio between two consecutive changes of the cost functions becomes smaller than a given parameter α ($\alpha = 0.5$ in this paper). The following procedure describes the details of this extension:

(1) Initialize the number of SAPs M by its lower bound: $M = N_{LB}^{SAP} = \lceil \frac{N}{S} \rceil$.

(2) Find the best SAP set that minimizes the cost function E for M, by applying the SAP selection algorithm in the previous section, and set $E_M = E$.

(3) Calculate the change of E by the increase of M, if $M \geq N_{LB}^{SAP} + 1$: $\Delta E_M = E_{M-1} - E_M$.

(4) Output the best SAP set with $M - 1$ SAPs, and terminate the procedure, if $M \geq N_{LB}^{SAP} + 2$ and $\Delta E_M / \Delta E_{M-1} < \alpha$.

(5) Otherwise, increment M by 1 and go to (3).

4 Evaluation by Simulations

In this section, we evaluate the effectiveness of the proposed algorithm extension through solving four instances. For the first three instances, we use the same grid topology with different traffic loads shown in Figs. 3-5. The GW has wireless links with its eight neighbor APs so that the maximum of eight NICs/channels can be assigned to the GW in the ideal case. The other APs have links with four neighbor APs among them. The AP depicted by a gray circle is associated with 8 hosts for pattern 1, 10 hosts for pattern 2, and 4 hosts for pattern 3. In any instance, the AP by a white circle is associated with 1 host.

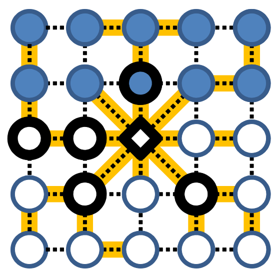

Figure 3: Grid topology and traffic load for pattern 1.

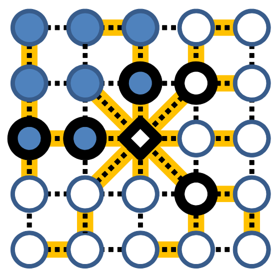

Figure 4: Grid topology and traffic load for pattern 2.

For the last instance, we adopt a more practical topology modeling the main floor in Okayama station in Fig. 6. In the last instance, the AP allocation and traffic loads are given by considering the floor plan and the flow of people there. We note that the number inside a circle represents

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the expected maximum number of hosts at the AP. The AP around the field center is selected as the GW where no host is associated.

In any instance, the WDS cluster size S is set 8, the number of channels P is 10, and the maximum number of NICs per SAP Q is 10, so that any link incident to the GW can be assigned a different channel to maximize the throughput. The AP marked by a bold line represents a selected SAP and the bold line between two APs represents the link included in the routing tree found by our algorithm.

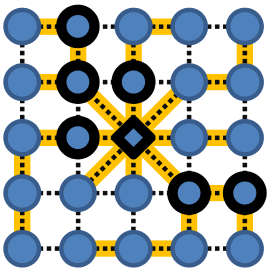

Figure 5: Grid topology and traffic load for pattern 3.

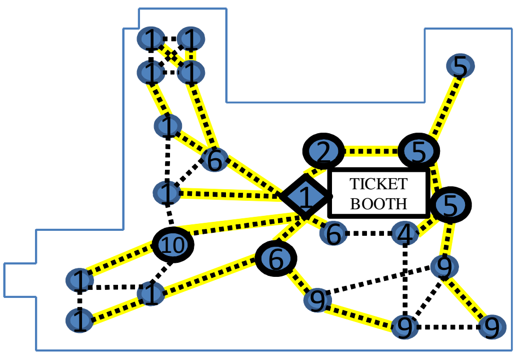

Figure 6: Okayama station topology and traffic load.

For each instance, we apply the proposed algorithm to find the minimal SAP set with the maximal throughput. Then, to confirm the validity, we find the best SAP set for each different number of SAPs, and evaluate the throughput by packet transmission simulations using the WIMNET simulator [2][3]. In each simulation, every host posses 125 packets to the GW (Internet) and the GW does 1,000 packets to every host before starting it. Then, after every packet reached the destination, the throughput is calculated by dividing the total packet size with the simulation time. The bandwidth is set $30Mbps$ for any link between two APs and $20Mbps$ for that between an AP and a host. When multiple links within interference ranges try to be activated simultaneously, randomly selected one link among them is successfully activated, and the others are inserted into waiting queues.

Figures 7-10 show the change of the cost function and the throughput for each of the three instances with the grid topology and the Okayama station topology, respectively, when the number of SAPs is increased one by one. In the three grid instances, the lower bound on the number of SAPs is 4 from $\lceil \frac{25}{8} \rceil = 4$, and in the station instance, it is 3 from $\lceil \frac{23}{8} \rceil = 3$. In any instance, as the number of SAPs increases, the cost function decreases and the throughput increases, where they are saturated at a certain number of SAPs.

Table 1 summarizes the number of SAPs in the solution by our algorithm and its throughput error to the maximum throughput for each instance. The throughput error is less than 3% in any instance. Note that the maximum throughput is given by selecting every AP as a SAP in each instance, and the error is given by $(b-a)/b \times 100\%$ where a is the throughput of the solution and b is the maximum one.

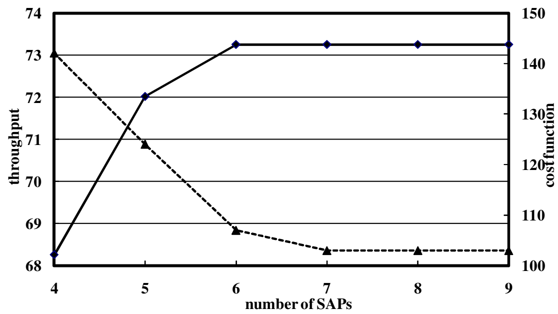

Figure 7: Simulation result for grid topology with traffic pattern 1.

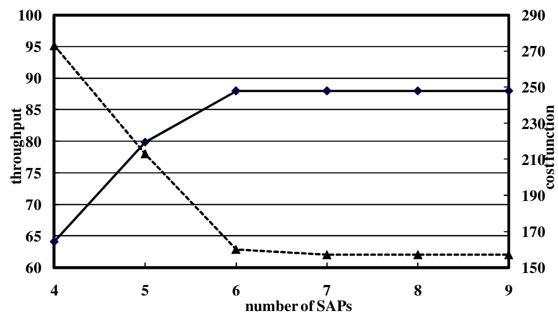

Figure 8: Simulation result for grid topology with traffic pattern 2.

5 Conclusion

This paper presented the extension of the smart access-point (SAP) selection algorithm to finding the minimal

Table 1: Solution quality of SAP set selected by algorithm.

topology	algorithm			maximum	
(traffic pattern)	# of SAPs	throughput(Mbps)	error(%)	# of SAPs	throughput(Mbps)
grid (1)	6	73.247	0.0	25	73.247
grid (2)	6	87.968	0.0	25	87.968
grid (3)	7	119.98	2.59	25	123.169
station	6	97.328	1.137	23	98.447

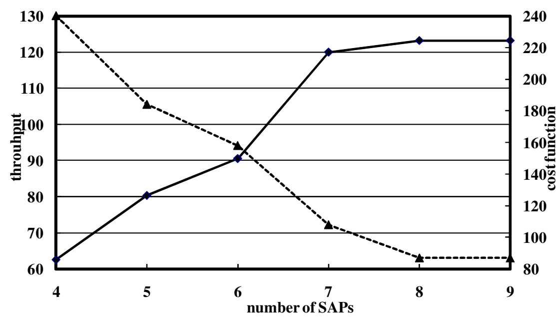

Figure 9: Simulation result for grid topology with traffic pattern 3.

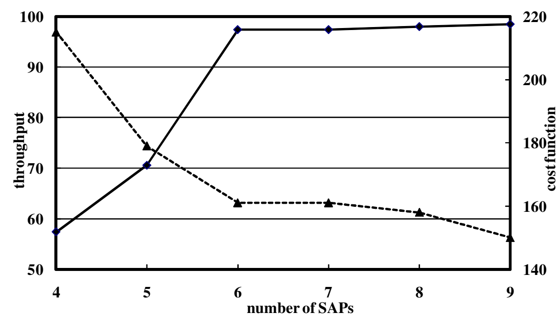

Figure 10: Simulation result for Okayama station topology.

SAP set with the maximal throughput for the wireless Internet-access mesh network *WIMNET*. The effectiveness was verified through simulations in four instances using the WIMNET simulator. Our future works may include further extensions of the SAP selection algorithm to dynamic changes of traffic loads and/or network topology by failures of links/APs, and their evaluations in real networks after implementing the SAP.

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