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A Two-Stage Algorithm for Access Point Allocation in Indoor Environments for Wireless Mesh Networks

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***Abstract*— As a flexible, inexpensive large-scale access network to the Internet, we have studied *WIMNET (Wireless Internet-access Mesh NETwork)*. WIMNET is composed of multiple access points (APs) as wireless routers, where each AP has multihop wireless connections with others by the wireless distribution system (WDS). In WIMNET, communications between APs and the Internet gateway can become the bottleneck due to multihop link activations. Besides, the link quality in indoor environments may be degraded by obstacles such as walls. Thus, the proper allocation of APs is essential, such that the installation cost and the maximum hop count between APs should be minimized while any host in the service area must be covered by at least one AP. In this paper, we formulate this AP allocation problem in indoor environments for WIMNET, and present its two-stage heuristic algorithm composed of the initial AP allocation and the AP allocation optimization with the association host optimization. The effectiveness of our approach is verified through extensive simulations using our WIMNET simulator.**[1]

I. INTRODUCTION

Currently, the Internet has become increasingly important in our everyday lives. One main factor of this progress comes from rapid developments of inexpensive small-sized communication devices and the high-speed communication technology. As a result, a variety of information, data, and services have been provided through the Internet, leading to strong demands of high-speed, inexpensive, and flexible Internet access services in any place at anytime. Particularly, these demands have grown up among users using wireless communication devices.

A common solution to meet these demands is the use of the wireless local area network (WLAN). Actually, WLAN has been widely studied and deployed as an access network to the Internet. WLAN has become available in a lot of Internet service spots in offices, schools, homes, airports, stations, and shopping malls. Along this context, the *wireless mesh network* has emerged as a very attractive technology that can flexibly and inexpensively expand the limited scale of a single WLAN [1]. The wireless mesh network is composed of multiple wireless routers that are distributed in the service area, because the coverage area by a single wireless router is limited to a small space. In this network, data communications between routers, in addition to those between hosts and APs, are offered by multihop wireless communications.

Among several variations of under-studying wireless mesh networks, our study has focused on the one that uses access points (APs) as wireless routers and realizes communications between APs mainly on the MAC layer by the *wireless distribution system (WDS)*. At least one AP in WIMNET acts as a gateway (GW) to the Internet. For the optimal design of WIMNET, we have studied several optimization problems and their algorithms. We defined the gateway AP selection problem and presented its algorithm [2]. We defined the channel configuration problem with its algorithm [3].

In WIMNET, the packets to/from user hosts, if associated with APs other than GWs, must reach one of GWs through multihop communications between APs to access the Internet. Hence, in the AP allocation stage, all the APs must be connected to at least one GW directly or indirectly. Besides, any host in the field must be covered wirelessly by at least one AP. On the other hand, the number of installed APs should be minimal to reduce the installation and operation costs. Furthermore, the maximum hop count between APs should be minimized to improve the connection quality and the overall throughput [4]. Thus, a proper AP allocation that satisfies these demands is very important. This optimization task of the AP allocation can be formulated as a combinatorial optimization problem.

In this paper, we present a formulation of the AP allocation problem in WIMNET. Then, we propose the two-stage heuristic algorithm, composed of the initial AP allocation and the AP allocation optimization, with the association host optimization to satisfy the complex constraints while optimizing the objectives. The first stage of our algorithm finds an initial feasible AP allocation by a greedy method that is a typical heuristic algorithm without iterations. This stage includes additional AP allocations to satisfy the load constraint of APs. The second stage improves the initial AP allocation by repeating small changes of AP allocations and AP transmission powers. This stage includes the refinement of the associated AP to every possible host for the better load balance and communication quality. The effectiveness of our approach is evaluated through simulations using the WIMNET simulator [5] that has been developed by our group.

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The rest of this paper is organized as follows: Section II formulates the AP allocation problem. Section III presents our algorithm. Section IV discusses our simulation results using the WIMNET simulator. Section VI provides the conclusion and future works.

II. FORMULATION OF AP ALLOCATION PROBLEM

In an indoor environment, the wireless connection is strongly affected by obstacles such as walls, whereas the precise effect estimation is very hard for all the points in the service area. Thus, we adopt a discrete formulation of evaluating wireless connections in the indoor environment.

A. Network Model

A closed area such as one floor in an office building, a library, and a conference hall, is considered as the network field for WIMNET. On this field, discrete points called *host points* are considered as locations where hosts and APs may exist. Every host point is associated with the number of possibly located hosts there. Besides, a subset of host points are given as *battery points* where the electricity can be supplied to operate APs. Thus, AP allocations must be selected from battery points. In the design phase of WIMNET, several battery points can be available as gateways to the Internet. This gateway selection is also an important mission of the AP allocation.

The network field usually consists of several rooms that are surrounded by walls. To consider the effect of walls in the transmission power attenuation, we adopt a simple formula, where if the i-th AP (AP_i) can cover up to the distance d from its position with the sufficient wireless signal, the covering capability distance after passing n walls will reduce to d':

$$d' = \frac{d}{1+n^2}. \tag{1}$$

B. Objectives

A proper WIMNET construction must consider the AP installation cost [6], while providing the performance optimality [7]. Because routing protocols usually focus on finding paths with the minimum hop count, our AP allocation should aim to minimize the maximum hop count to the GW (gateway AP) from each AP. Besides, the maximum load limit for any AP should be satisfied to enforce a load balance between APs, because the proper load balance among APs may affect the overall performance [8]. Furthermore, the signal transmission power of APs should be minimized to reduce the AP operation cost and the interference of link activations with the same channel. Here, to reduce the interference and enhance the throughput, the multi-channel system for communications between APs has been also considered in WIMNET [9]. Hence, our objects are summarized as follows:

- to minimize the number of installed APs,
- to minimize the maximum number of hops (hop count) to reach a GW from any AP (find the shortest route), and
- to minimize the transmission power range of each AP.

C. Problem Formulation

Now, we define the AP allocation problem for WIMNET.

- **Input:** A set of host points $H = \{(hx_i, hy_i)\}$ with the expected number of hosts hn_i at host point h_i, a set of battery points $B = \{(bx_j, by_j)\} \subseteq H$ with the AP installation cost bc_j at battery point b_j, a set of gateway candidate $GS \subseteq B$, a set of walls $W = \{(wsx_k, wsy_k, wex_k, wey_k)\}$, the association host limit for one AP L, and a set of AP transmission ranges P, a selected battery point to be the $GW \in GS$.
- **Output:** A set of battery points for AP allocations S with selected wireless ranges p_i for each AP.
- **Constraint:** To satisfy the following five constraints:
  1) to cover every host point by an AP,
  2) to connect every AP to GW directly or indirectly,
  3) to allocate APs only at battery points,
  4) to select one power range from P for each AP, and
  5) to associate L or less hosts for each AP.
- **Objective:** To minimize the following cost function:

$$E = \alpha \sum_{j \in S} bc_j + \beta \ \max\{hop\_to\_GW\} + \gamma \sum_{j \in S} p_j / |S| \tag{2}$$

where α, β and γ are constant coefficients. The α-term represents the total installation cost of APs, the β-term does the maximum hop count to GW from the APs, and the γ-term does the average transmission power.

III. AP ALLOCATION ALGORITHM

In this section, we propose a two-stage heuristic algorithm. This algorithm finds an AP allocation with the smallest cost function for a given $GW \in GS$.

A. Initial AP Allocation Stage

After initialized S with GW, this stage finds an initial set of battery points S for a given input through two steps.

1) Host Coverage Step: A battery point b_j that satisfies the following four conditions is selected into S as a new AP allocation:

1) b_j is not included in S,
2) b_j is connected with at least one AP in S,
3) b_j can cover the maximum number of uncovered hosts (the sum of expected numbers of hosts of uncovered host points), and
4) b_j has the largest number of incident wireless links (maximum degree) for tie-break, if two or more APs become candidates in 3).

This battery point selection is repeated one by one until every host point h_i is covered by an AP in S. Here, each time a new battery point is selected, the host point coverage by the installed APs and connections between APs are evaluated by their transformed distances counting the existence of the walls. Then, the maximum transmission power is selected for each selected battery point.

2) Load Balance Step: The above step may not satisfy the last constraint (the load constraint) of the problem. To satisfy this constraint, different battery points are additionally selected into S to reduce the loads of the APs that do not satisfy the constraint. The selection procedure is as follows:

1) Associate one AP to each host point such that the transformed distance is minimum among covering APs.
2) Calculate the number of hosts associated with each AP.
3) Terminate the procedure if every AP satisfies the load constraint.
4) Select battery points closest from the APs that do not satisfy the AP load constraint (i.e. they are associated with more than L host points) into S, and go to 1.

After these steps, the initial cost function E is calculated from the initial AP allocation.

B. AP Allocation Improvement Stage

This stage improves the AP allocation iteratively, by changing one randomly selected decision variable (AP allocation or AP transmission power) at each iteration.

1) AP Allocation Case: If the AP allocation is selected, the following procedure is applied:

1) Randomly select new battery point b_j that is not selected in S and is connected to an AP in S, and add it into S.
2) Set the maximum transmission power for this new AP allocation.
3) Apply the association host optimization in Section III-B3.
4) Remove from S the APs that satisfy the following five conditions:
    a) it is different from this new battery point b_j and GW,
    b) all the host points can be covered by the remaining APs if removed,
    c) all the APs can be connected directly or indirectly to GW if removed,
    d) a better cost function E value is obtained if removed, and
    e) the load constraint is satisfied if removed.

2) AP Transmission Power Case: If the AP transmission power is selected, this transmission power is changed into the least one in P, such that its associated hosts are covered by it, even after reducing the transmission power.

3) Association Host Optimization: Some host points might be associated with farther APs, although they can be associated with nearer APs in terms of the transformed distance. These host points are re-associated with best APs by the following steps:

1) Find the better APs with the smaller transformed distance for every host point.
2) Repeat the change of the associated AP for every host point associated with a different AP from the best one until no more host point can be changed:
    a) Move the association to the better AP, if its load is smaller than the upper limit.
    b) Swap the associated APs between two host points, if the opposite associations of this pair is better for them.

IV. PERFORMANCE EVALUATION

In this section, we discuss performance evaluations of our approach to the AP allocation in two typical network fields for WIMNET, through network simulations using the WIMNET simulator.

A. WIMNET Simulator

The WIMNET simulator simulates least functions for wireless communications of hosts and APs that are required to evaluate throughputs and delays, because it has been developed for evaluations of a large-scale WIMNET with reasonable CPU time on a conventional PC. Thus, a sequence of functions such as host movements, communication request arrivals, and wireless link activations, are synchronized by a single global clock called *a time slot*. Within an integral multiple of time slots, a host or an AP can complete the one-frame transmission and the acknowledgement reception. The duration time of one time slot is $0.2ms$. From our past experimental results, the maximum transmission speed between APs is set $30Mbps$, and that between an AP and its associated host is $20Mbps$. Note that this transmission rate can cover about 26 hosts [10][11]. In the simulator, the former link is completed with two slots, and the latter is with three slots, assuming every frame size is $1,500bytes$. When two or more links within their wireless ranges may be activated at the same time slot, randomly selected only one link among them is successfully activated, and the others are inserted into waiting queues to avoid collisions, supposing DCF and RTS/CTS functions.

Before starting each simulation, every host point has $1,000$ packets transmitted to GW, and GW has 125 packets to every host. When every packet reaches the destination or is lost, the simulation is finished. The packets for each request are transmitted along the routing path by our algorithm. Only the connection-less communication is implemented in the WIMNET simulator, where the retransmission between end hosts is not considered.

B. Simulation Results for Network Field 1

1) Network Field: Our first network field is composed of 16 rooms with the same size and a corridor between the two rows of rooms. Each room has 5×10 meters, where 15 host points are distributed regularly. The host points along horizontal walls are selected as battery points. In addition, 9 battery points are allocated in the corridor where the center one is selected as GW. Fig. 1 shows this network field, where a circle represents a battery/ host point, and a dot represents a host point. The maximum load constraint is set 25 host points, and the maximum wireless rang is set $90m$. The wireless range is also illustrated in the figure using the dashed curve in the network field, by applying the formula in Eq.(1) considering the wall effect. If there is no wall effect, one AP can cover all the network field.

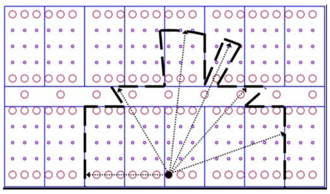

Fig. 1. Network field 1 and wireless range.

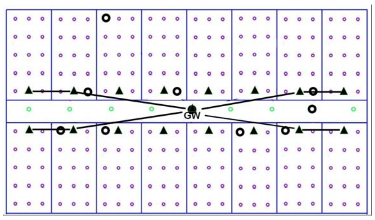

Fig. 2. AP allocations with two-hop routes for network field 1.

2) AP Allocation Quality: First, the solution quality by our algorithm is evaluated in terms of the number of installed APs and the maximum hop count. For this purpose, our solution is compared with a simple manual solution of allocating one AP at each room to cover the network field. Fig. 2 shows AP allocation results in two solutions, where big circles represent our AP allocations and triangles represent manual AP allocations. In the manual solution, the four APs in both end rooms need two hops to GW as shown in the figure.

Table I summarizes the quality of two solutions, in addition to the lower bounds on the number of APs to cover the network field and the maximum hop count to GW. The lower bound on the number of APs is given by:

$$\left\lceil \frac{240(=\#\ of\ hosts)}{25(=Max.\ load\ per\ AP)} \right\rceil = 10. \qquad (3)$$

Thus, our algorithm can find the lower bound solution.

3) Network Performance: To evaluate the communication quality of the AP allocation, the total throughput is observed by the WIMNET simulator. The throughput is calculated by dividing the total amount of received packets by the simulation time, where the average result among ten simulation runs using different random numbers for packet transmissions is used to avoid the bias of random number generations. Here, multi-channel links are considered to practically enhance the throughput for AP communications. Each AP may be assigned with more than one NICs (Network Interface Cards), and then, proper channels are assigned to the links by our previous NIC/channel assignment algorithm [3]. Fig. 3 compares average throughputs by the manual solution, the 1st stage of our algorithm, and the both stages of our algorithm with different numbers of NICs or channels at GW. In any case, our average throughput is better than that of the manual one. Here, we note that the throughput is saturated at two channels used at GW, because communications between hosts and APs become the bottleneck instead of communications between APs.

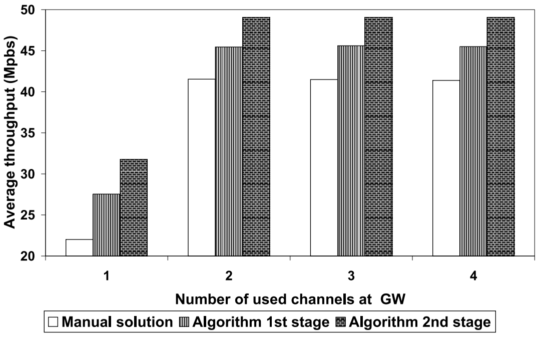

Fig. 3. Comparison of throughputs for network field 1.

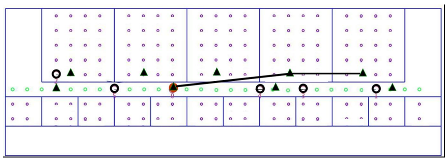

Fig. 4. AP allocations with two-hop route for network field 2.

C. Network Field 2

The second network field is composed of two rows of 17 rooms with different sizes and a corridor between them. Each room in the first row has 10×10 meters with 20 host points, and that in the second row has 5×5 meters with four host points, except for one room with two host points. Thus, the total of 146 host points are distributed regularly in these rooms, where the host points along horizontal walls are selected as battery points. The maximum load constraint is set 25 host points. Fig. 4 shows our AP allocation (big circles) and the manual one (triangles). In the manual allocation, one AP is allocated to each big room and four APs are allocated to the corridor regularly for simplicity. The AP in one end room needs two hops to GW.

Table I summarizes the quality of two solutions, where our algorithm again finds the lower bound solution. Fig. 5 compares average throughputs by the three methods with different numbers of NICs or channels at GW, where our throughput is always better than that of the manual one.

D. Effect of Coefficients in Cost Function

The effect of the coefficients in the cost function in Eq.(2) is investigated. After several simulations, we found that any change in α, β and γ does not affect the final results. This is because our algorithm seeks the better value for each term of the cost function step-by-step.

TABLE I
COMPARISON OF SOLUTION QUALITY FOR NETWORK FIELD 1.

	Number of allocated AP	Max. hops to the GW
Lower bounds	10	1
Manual solution	17	2
Our algorithm	10	1

TABLE II
COMPARISON OF SOLUTION QUALITY FOR NETWORK FIELD 2.

	Number of allocated AP	Max. hops to the GW
Lower bounds	6	1
Manual solution	9	2
Our algorithm	6	1

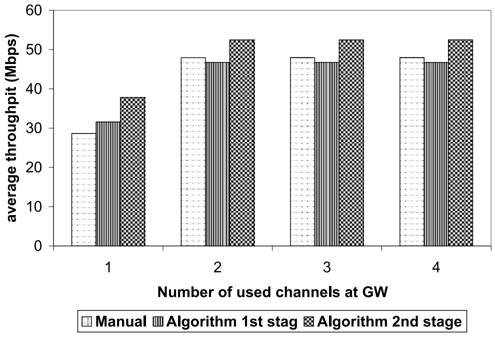

Fig. 5. Comparison of throughputs for network field 2.

V. RELATED WORKS

Several papers have reported various proposals of optimization-driven AP placement algorithms in conventional WLANs. Within our knowledge, the AP allocation problem in the wireless mesh network for the Internet access in indoor environments like WIMNET has not been considered before. In fact, most of these articles focus on the construction of WLAN without considering the wireless connection between APs.

[10] has studied the problem of designing a WLAN, and proposed an optimization model for selecting the location as well as the power and the channel for each AP. A Tabu search algorithm for improving this solution has been proposed. The results were compared to a lower bounds obtained by relaxing a subset of the constraints in their model. Their results have shown that this heuristic produces relatively good solutions rapidly. It is significant to develop the lower bound formulation in order to evaluate precisely the proposed heuristic, and to explore exact algorithms to solve small-size instances of the problem.

[12] focuses on the AP placement problem and the channel assignment problem to minimize the maximum of the channel utilization, which are solved by an optimization solver without considering the indoor environment.

[13] investigates the AP allocation problem, and presents a global optimization algorithm to solve the mathematical model of the problem. Their results indicate that the model can be used for finding the optimal number of APs and their placements while covering every location of the network field. They observed that the dimension of the building, the number of users and their locations, the transmission power, and its received threshold have effects on the AP allocation.

[14] formulates the Internet transit access points placement problem under various wireless models. This problem aims to provide the Internet connectivity in multihop wireless networks. If we consider the Internet transit access point as a gateway, their network model is the same as WIMNET where every AP becomes GW.

VI. CONCLUSION

This paper has presented the formulation of the AP allocation problem in the indoor environment of the wireless Internet-access mesh network called WIMNET, and its two-stage heuristic algorithm composed of the initial AP allocation and the AP allocation optimization with the association host optimization. The effectiveness of our approach is verified through network simulations using the WIMNET simulator. The significant performance improvement over manual simple AP allocation is observed. Our future works may include more precise considerations of the effect of indoor environments by using a propagation model [15], and comparisons of our approach with existing ones for the same or related problems.

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