Time Slot Assignment for Maximum Bandwidth in a Mobile Ad Hoc Network

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***Abstract*—Time slot assignment is essential to provide the calculated bandwidth in a TDMA (Time Division Multiple Access)-based mobile ad hoc network (MANET), which is a focus of attention of this paper because of its collision-free packet transmission with QoS(Quality of Service) support. In this paper, a new time slot assignment algorithm-SAGO (Slot Assignment by Global Overview) is proposed, by which more available bandwidth can be obtained than conventional approximate solutions. SAGO assigns time slots from a global overview, that is, time slot assignment is based on the usage of global information such as finding of bottleneck of a route, tentative bandwidth evaluation of a route and assignment of time slot according to the order of their free times in the concerned links. In addition, SAGO's effectiveness is proved by simulation results.**

***Index Terms*—Ad hoc network, MANET, QoS, bandwidth guarantee, time slot assignment**

I. Introduction

A mobile ad hoc network (MANET[1]-[3]) is an autonomous system of mobile nodes connected by wireless links. The nodes communicate with each other over a wireless medium without the intervention of centralized access points or base stations. Each node acts both as a router and as a host.

The applications of MANET are drawing more and more attention in a civilian life for complements of the Internet. Recently, providing required bandwidth for these applications in MANETs has become an unavoidable and urgent task to achieve sufficient QoS (Quality of Service) because of the rising popularity of multimedia applications and potential commercial usage of MANETs([3]-[7]).

TDMA (Time Division Multiple Access) is a technology for shared medium (including radio) networks. It allows several users to share the same frequency medium by dividing it into different time slots. The users transmit data in rapid succession, one after the other, each using its own time slot. TDMA deterministic scheduling is preferred for networks with heavy load carrying mixed traffic and TDMA is suitable for collision-free packet transmission with QoS support. Therefore, the research on TDMA-based MANETs has attracted more and more attention.

Synchronization is a very critical issue for all distributed TDMA systems. A possible solution, now at low cost, consists in making use of the GPS (Global Positioning System) that provides a global synchronization for all nodes. Also the European satellite navigation system GALILEO will provide a very good timing accuracy [8]. Another way is local synchronization, where the nodes try to synchronize themselves by exchanging beacons with their neighborhood [9][10]. Thus, nowadays synchronization is not a difficult problem.

In order to provide enough bandwidth for multimedia applications, bandwidth calculation is firstly necessary for the routes through which multimedia data are transferred [11][12]. Moreover, bandwidth for a route is measured in terms of the number of free time slots available in TDMA-based MANETs [13]-[15]. Thus, time slot assignment is essential to provide the calculated bandwidth for a route in a TDMA-based MANET, which is a focus of attention of this paper because of its collision-free packet transmission with QoS support [13] [16] [17].

In a TDMA-based MANET, different bandwidths for a route can be obtained by different time slot assignment algorithms. Our research aims to find an effective time slot assignment algorithm by which more available bandwidth for a route can be obtained than existing solutions.

The rest of the paper is organized as follows. Section II briefly describes the research model and formulates the problem of time slot assignment for maximum bandwidth of a route in a mobile ad hoc network. Section III introduces the related works of time slot assignment and analyzes their demerits. In Section IV,

Based on "Time Slot Assignment for Maximum Bandwidth in a Mobile Ad Hoc Network", by Jianping Li and Yasushi Wakahara, which appeared in the Proceedings of International Symposium on Wireless Pervasive Computing, Puerto Rico, USA, Feb. 2007

our proposal of new time slot assignment is presented with its detailed description. Simulation results are provided in Section V to demonstrate the effectiveness of our proposal. Section VI concludes the paper and presents the future work.

II. Research Model and Formulation of Time Slot Assignment

The model in this paper research is described as follows:

Assumption 1: *A route in a mobile ad hoc network is established by a reactive routing protocol, for example, DSR(Dynamic Source Routing).*

A shortest route or a minimum hop route is selected by the protocol. When route request packets are transferred in a mobile ad hoc network, the information of already assigned and used time slots can be gathered at the same time. Using this information of time slots, time slots of the route can be assigned in either of the two end nodes in order to obtain the maximum bandwidth of the route.

Assumption 2: *Each node is equipped with only one transceiver with an omni antenna, and it can not send data and receive data at one time.*

Because of one transceiver, a node can not receive data from many nodes in a same time slot. Fig. 1 shows an example of this assumption.

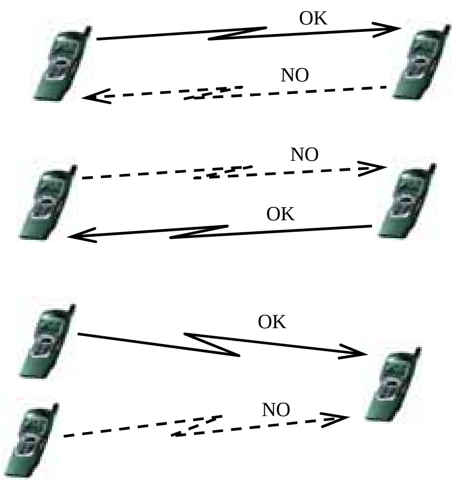

Figure 1. An example of Assumption 2

Assumption 3: *The interference range Ri of a node is equal to its transmission range Rt, that is, Ri = Rt. See Fig. 2.*

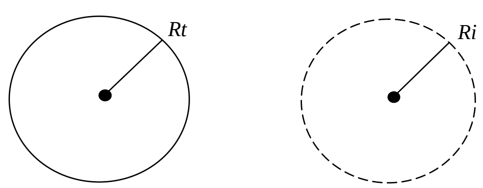

Figure 2. Interference range and transmission range

Fig. 3 shows an example of a shortest route with five nodes, where only direct adjacent nodes of a node are within the transmission range of the node. According to the above assumptions, in Fig.3, using a same time slot, when node A sends data to node B, node B can not send data to node C(if so, there will be an interference at node B because of the simultaneous sending and receiving), and node C can not send data to node D(if so, there will be an interference at node B because of the simultaneous receiving from node A and node C), but node D can send data to node E at the same time(there is no interference at any node). So the using ratio of time slots is generally only one-third of total time slots.

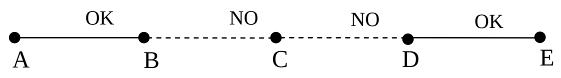

Figure 3. A route of five nodes

Definition 1*: Link bandwidth.*

The number of common free slots between two adjacent nodes denotes the link bandwidth between them.

For example, in Fig.4, consider two adjacent nodes, node A and node B, having free slots FS(A)={1, 2, 4, 5, 6, 7} and FS(B)={1, 3, 5, 8} respectively. FS(X) is defined from the viewpoint of node X as the set of slots which are not used by any adjacent nodes of node X (to receive or to send). The link bandwidth LinkBW(A,B)=|FS(A) ∩ FS(B)|=|{1, 5}|=2. It means that only slots 1 and 5 can be used by nodes A and B for transmitting data packets to each other.

In the following, we will directly use the link bandwidth to calculate the available bandwidth of a route, instead of free slots of every node.

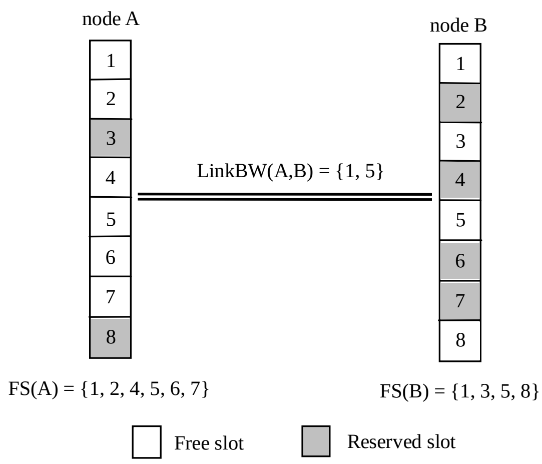

Figure 4. An example of link bandwidth

Definition 2: Route bandwidth.

With some proper algorithm for time slot assignment, free time slots of every link of a route can be assigned without conflict, and the number of assigned time slots of every link of the route is equal. This number of available time slots is denoted as the route bandwidth.

In Fig. 5, the bandwidth of the route A-B-C-D-E is equal to 1.

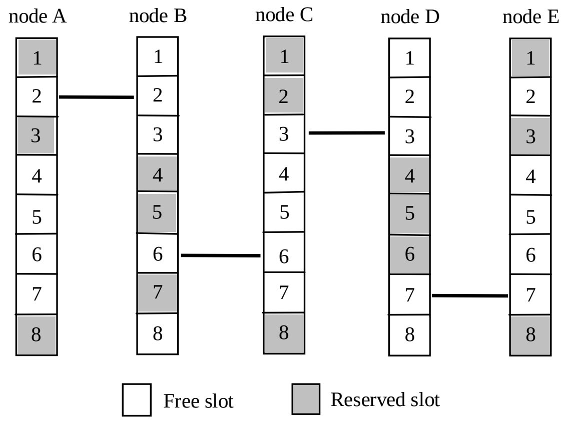

Figure 5. An example of route bandwidth

Formulation of time slot assignment: Time slot assignment is a MIP (Mixed Integer Programming) problem. Its optimal solution can be derived by linear programming tools.

The purpose of time slot assignment is to assign as many time slots of every link as possible in order to get the maximum bandwidth of a route. This problem can be formulated as follows.

Suppose there is a route of N (integer) links, and there are K (integer) slots in a time cycle, that is, the maximum number of free time slots in every link is K.

$$\max \sum_{j=1}^{K} x(i,j) \qquad \text{(i=1,…,N)} \quad (1)$$

$$\sum_{j=1}^{K} x(1,j) = ... = \sum_{j=1}^{K} x(i,j) = ... = \sum_{j=1}^{K} x(N,j) \quad (2)$$

$$x(i,j) + x(i+1,j) + x(i+2,j) \le 1 \quad \text{(j=1,…,K)} \quad (3)$$

$$a(i,j) + x(i,j) \le 1 \quad (4)$$

x(i,j) : the result of time slot assignment. It shows that the slot j(between 1 and K) of link i(between 1 and N) is assigned or not for the route. It has two values: 1 and 0. The value of 1 represents that this slot is assigned for the route, and the value of 0 represents that this slot is not assigned for the route.

a(i,j) : the status of the slot j(between 1 and K) of link i(between 1 and N) at the moment of assignment. It is the known information for the route. It also has two values: 0 and 1. The value of 0 represents that this slot is free, and the value of 1 represents that this slot is not free.

Formula (1) is to maximize the bandwidth of the route; formula (2) shows every link bandwidth of the route is equal according to Definition 2; formula (3) shows a same time slot can not be assigned two or more times in three successive links of the route according to Assumption 2; and formula (4) means that only free time slots of every link can be assigned. According to these formulas, optimal time slot assignment with maximum available bandwidth can be obtained by linear programming tools such as GLPK (GNU Linear Programming Kit) [18]. This kind of method is named as MIP method.

The model file of this MIP method for GLPK is as follows.

```
#assign.mod
param N;
param K;
param p := N-2;
set Link := 1..N;
set Slot := 1..K;
set S_link := 1..p;

param a{Link,Slot} binary;

var x{Link,Slot} binary;
var max integer, >= 0;

maximize BANDWIDTH{i in Link}:
                          sum{j in Slot}X[i,j];

s.t. Link_bandwidth{i in Link}:
            sum{j in Slot}x[i,j] = max;
s.t. Path{p in S_link, j in Slot}:
            (x[p,j]+x[p+1,j]+x[p+2,j]) <= 1;
s.t. SameSlot{i in Link, j in Slot}:
            (a[i,j]+x[i,j]) <= 1 ;
```

where, N is the number of links in a route, and K is the total number of slots in each link. a[i, j] represents the status of a slot in a link. If a[i, j], the known information, is equal to 0, the slot is free, or else it is not free, that is, it is used by other links. x[i, j], the result of time slot assignment, is the flag to show whether the slot is assigned for the route or not. If x[i, j] is 1, the slot is assigned; if x[i, j] is 0, the slot is not assigned for the route.

With a model file and a data file as input, the corresponding optimal time slot assignment result can be derived.

III. Related Works

Though optimal time slot assignment for maximum bandwidth can be obtained by MIP method, it takes too much time to complete the time slot assignment when a MANET becomes large, which leads to the infeasibility of MIP method in practice.

Thus, an approximate method is practically necessary in order to overcome the shortage of MIP method and to meet the need of bandwidth for multimedia application in a MANET.

References [19]-[21] are related works for such approximate methods. The typical one of [20] is introduced here in detail. The algorithm presented by Chenxi Zhu in [20], denoted as Zhu's algorithm, lies in its distributed nature and simple iterative calculations. This algorithm iterates over the hops from the source to the destination. Fig. 6 shows an example application of Zhu's algorithm, in which the letters of A, B, C, D, E and F represent the nodes of the route and free time slots of every link are listed on the links of the route. The result of the application of Zhu's algorithm is given from Step 1 to Step 4 in this figure.

This method has the following demerits.

(1) The algorithm only performs localized search of available time slots, which ends up to sub optimality during the process of bandwidth calculation instead of searching over the entire route.

(2) There is a difference between the result by Zhu's algorithm, and the maximum result by MIP method. It can be confirmed from the simulation results in Section V because of its local searching during the process of time slot assignment.

(3) There is some probability of finding no assignment because of its local searching even when some assignment actually exists.

Fig. 7 shows an example of a route of five links. By Zhu's algorithm, the result of each step in the process of time slot assignment is shown in Table I.

TABLE I
AN EXAMPLE OF ZHU'S ALGORITHM APPLICATION

	LinkBW (A,B)	LinkBW (B,C)	LinkBW (C,D)	LinkBW (D,E)	LinkBW (E,F)
Step1	{1,3}	{2,5}			
Step2	{1}	{2}	{4}		
Step3		{2}	{4}	{1}	
Step4			{4}	{1}	NONE

In Step 4 of TABLE I, there is no available time slot for the route.

Thus, it is worthy to explore a better algorithm which performs global search in order to overcome the above demerits.

IV. PROPOSAL OF A NEW TIME SLOT ASSIGNMENT-SAGO

Suppose there is a route for transmitting multimedia data. It is assumed that the number of links of this route is known and free time slots of every link of this route are also known. It should be noted that the assignment avoids radio wave interference so that once a time slot of a link is assigned then the same time slots of its one-hop neighbor links and two-hop neighbor links cannot be assigned any more.

SAGO (Slot Assignment by Global Overview) performs the time slot assignment from a global viewpoint, whereas the conventional approximate methods do the assignment through the means of local searching. This global treatment of our proposal makes its assignment better approximation than conventional methods. The principles of this global treatment are as follows.

- The assignment trial is started from the bottleneck link that has the smallest number of free slots and is continued in other links towards both end links of the route.
- Time slot assignment is tried assuming a tentative value of available bandwidth.
- If the assignment trial becomes infeasible, the tentative value is decremented by 1 and the assignment trial is repeated until it becomes feasible.

The time slots for the assignment in a same link are selected according to the order of their free times in the concerned links, i.e. their one-hop and two-hop neighbor links.

SAGO can be described briefly by the following five steps. Table II is the notations in SAGO.

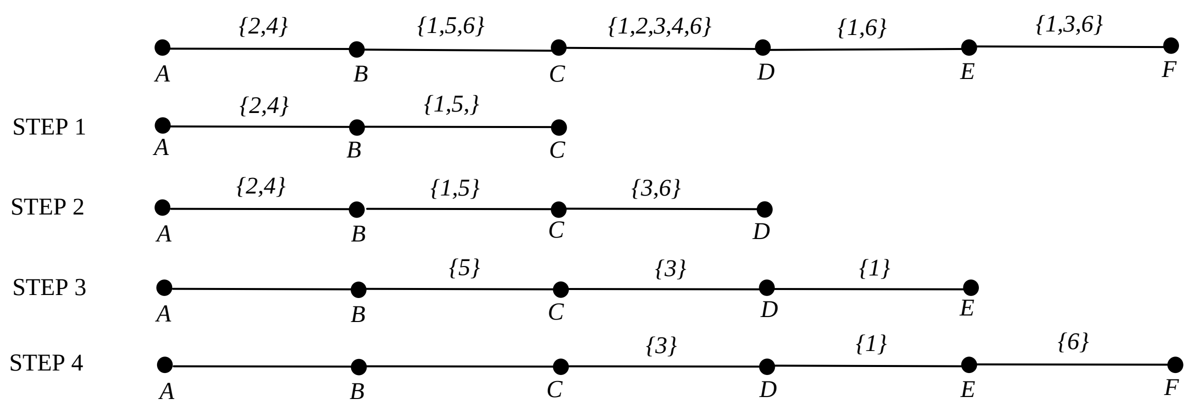

Figure 6. The bandwidth of a route calculated by Zhu's algorithm

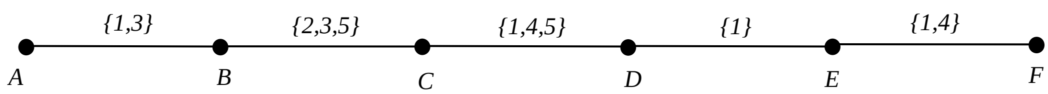

Figure. 7. An example of finding no assignment by Zhu's method

STEP 1. To find the starting link *s* from which the assignment will be started.

STEP 2. To calculate the tentative bandwidth *w*. of the route.

STEP 3. To begin time slot assignment from the starting link *s*, select *w* timeslots from the starting link *s*; the time slots which are not used by its one-hop and two-hop neighbors will be selected.

STEP 4. To continue to assign toward the destination node direction;

STEP 5. To continue to assign toward the source node direction.

TABLE II
NOTATIONS IN SAGO

NAME	MEANING
t	The number of total time slots
h	The number of links in a route
w	The tentative value of available bandwidth of a route
m	The number of bottleneck links that have the smallest number of free time slots in a route
s	The starting link from which time slot assignment is started
y	Criterion to indicate the degree of a slot's independence between a link and its neighbor links in terms of the common usage of the slot among the links
p	The minimum No. of all the bottleneck links of a route
q	No. of the link of minimum independence
g	The number of free time slots in the starting link
i	No. of the link in which the assignment is being done
r	Final assignment result, that is, the available bandwidth of the route

Note :No. of a link is its identifier.

The detailed description of SAGO is as follows:

```
BEGIN
m = CALCULATE_BOTTLENECK_LINKS;
if (m = 1)
  s = p;
else
   {
    independence=CALCULATE_INDEPENDENCE;
    s = q;
   }
w = SET_TENTATIVE_BANDWIDTH;
LABLE1:
i = s;
LABLE2:
SELECT_w_TIME_SLOTS;
if (SELECT_w_TIME_SLOTS = TRUE)
   {
     DELETE_w_TIME_SLOTS;
     if (i = h -1)
      {
        i = s -1;
        LABLE 3:
        SELECT_w_TIME_SLOTS;
        if (SELECT_w_TIME_SLOTS = TRUE)
          {
            DELETE_w_TIME_SLOTS;
            if (i = h -1)
            {
             r = w;
            exit(0);
            }
            else
            {
              i = i – 1;
             goto LABLE 3;
            }
          }
        else
          {
           w = w – 1;
          goto LABLE 1;
          }
      }
    else
        {
         i = i +1;
         goto LABLE2;
        }
   }
ELSE
{
  w = w -1;
     goto LABLE2;
}
END
```

The functions are explained as follows:

CALCULATE_BOTTLENECK_LINKS: To calculate the number (*m*) of bottleneck links that have the smallest number free time slots in the route;

CALCULATE_INDEPENDENCE: To calculate the independence (*y*) of every bottleneck link in a route. The independence of the bottleneck is determined by the following formula:

$$y = W1*number0 + W2*number1 + W3*number2 + W4*number3 + number4,$$

where, *W1*, *W2*, *W3* and *W4* are predefined constants and $W1>W2>W3>W4$, and $numberk(k=0,\dots,4)$ is the number of slots which are free for just k times in its concerned neighbors;

SET_TENTATIVE_BANDWIDTH: To evaluate the upper limit of the available bandwidth of the route by the following expression, and set it as the tentative value *w* for the available bandwidth;

$$w = min(t/3, g) \qquad (t=3,4,\dots)$$

SELECT_w_TIME_SLOTS: To select *w* time slots from the free time slots of link *i*. The time slots are selected according to the order of their free times in five successive links, that is, *link i-2, link i-1, link i, link i+1,* *link i+2*. The time slot of the fewest free times will be chosen.

DELETE_w_TIME_SLOTS: To delete above selected *w* time slots from the free time slots of one-hop and two-hop neighbor links of link *i;*

The flow chart of our proposal SAGO is given in Fig. 8.

Following the example in Fig.7 we show a complete process of time slot assignment by SAGO.

In STEP 1, we search the starting link from the route in Fig.7. In this route, the numbers of free time slots of the links are 2, 3, 3, 1 and 2 respectively from source to destination(Fig.9.(a)). Therefore, link(D,E) is taken as the only bottleneck link by the function of *CALCULATE_BOTTLENECK_LINKS* and this bottleneck link becomes the starting link of the route.

In STEP 2, we calculate the tentative bandwidth *w* of the route. In this example,

the number of total time slots:

$t = 5;$

and the number of free time slots in the starting link:

$g = 1;$

thus,

$w = min(t/3, g) = min(5/3,1) = 1.$

The above result is obtained by the function of *SET_TENTATIVE_BANDWIDTH*.

In STEP 3, we select one time slot from the starting link of link(D,E) by the function of *SELECT_w_TIME_SLOTS*. Because there is only one free slot in link(D,E), we assign this slot, that is slot 1, for link(D,E). See Fig.9.(b).

When slot 1 is assigned for link(D,E), it can not be assigned again in its concerned links, that is, its one-hop neighbors(link(C,D) and link(E,F)) and two-hop neighbors(link(B,C)). Thus, we delete slot 1 from link(C,D) and link(E,F) by the function of *DELETE_w_TIME_SLOTS*. See Fig.9.(c).

In STEP 4, we continue to perform the time slot assignment toward the destination node direction of the route. There is only one link: link(E,F) in this direction. Then we try to assign one slot for link(E,F). After slot 1 has been deleted from link(E,F), only slot 4 can be assigned for this link. Therefore, we assign slot 4 for link(E,F). See Fig.9.(d). Then we delete slot 4 from link(C,D) by the function of *DELETE_w_TIME_SLOTS*. See Fig.9.(e).

In STEP 5, we continue to perform the asssignment toward the source node direction. We try to assign the time slots for link(C,D), link(B,C) and link(A,B) in sequence.

First, we assign the slots for link(C,D). Because slot 1 and slot 4 has been deleted from this link, we assign slot 5 for it by the function of *SELECT_w_TIME_SLOTS*. See Fig.9.(f). Then we delete slot 5 from the concerned links of link(C,D), see Fig.9.(g).

Next, we try to assign the time slots for link(B,C). Because slot 5 has been deleted from this link, the slots which can be assigned are slot 2 and slot 3. In this condition, we consider the order of free times of each slot in their concerned links. Slot 2 is only free in link(B,C), but slot 3 is also free in link(A,B). Thus, the free times of slot 3 is more than that of slot 2. We choose slot 2 of fewer free times to be assigned for link(B,C). See Fig.9.(h).

Finally we try to assign the time slots for link(A,B). In this link, slot 1 and slot 3 are also free for once in their concerned links. They have same order. Thus we can select one slot for the link randomly. In this example, we select slot 1 for link(A,B). See Fig.9.(i).

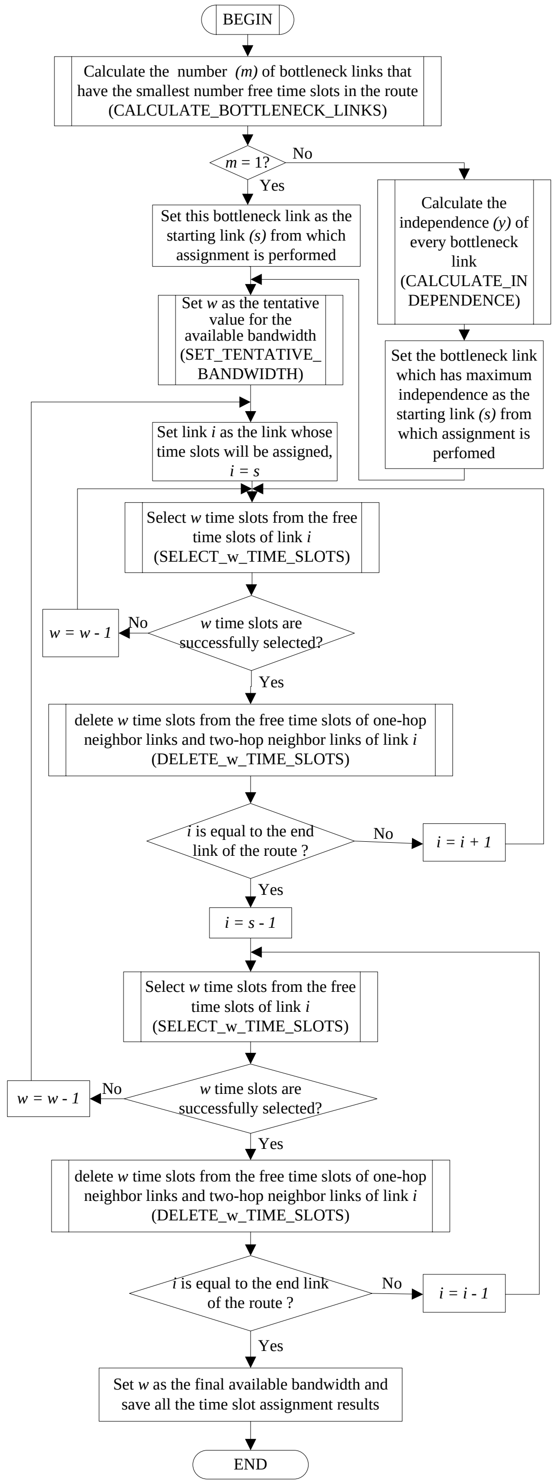

Figure 8. Flow chart of SAGO

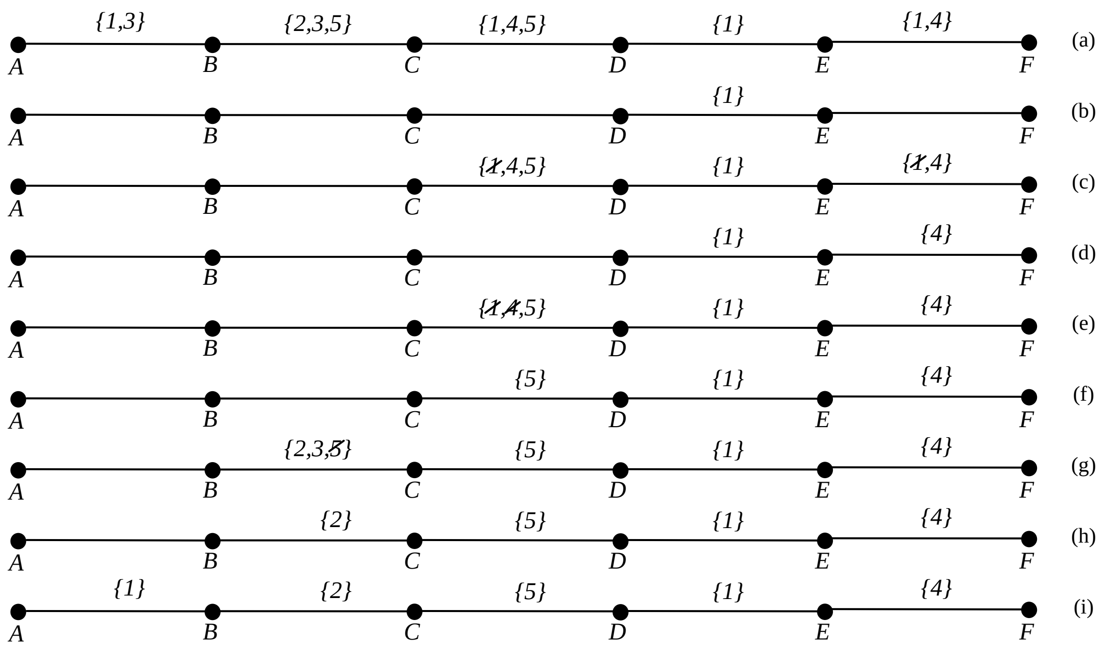

Figure. 9. A complete process of time slot assignment by SAGO

V. Evaluation by Simulation

By some experiments, the effectiveness of our proposed algorithm-SAGO is demonstrated. Fig.10 and Fig.11 show the simulation results of available bandwidth versus the ratio of free time slots in the given route in the case where the number of links is 10 and 30 and the number of time slots is 10 and 30 respectively for three time slot assignment methods: MIP method, conventional approximate method (Zhu's algorithm in [19] and [20]), and our proposal of SAGO. All the confidence intervals are less than 5% of the available bandwidth where the confidence level is equal to 95%. It is clearly observed that our proposed method achieves more available bandwidth than the conventional approximate method, and the results of the proposed method are very near those of the optimal solution by MIP method at most points of the ratio.

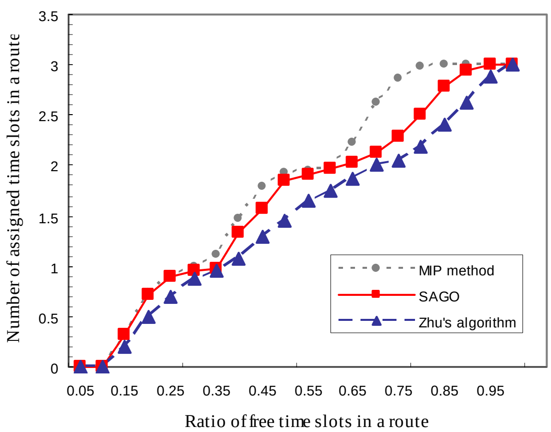

Figure 10. Comparison among three methods
Links: 10 Slots: 10

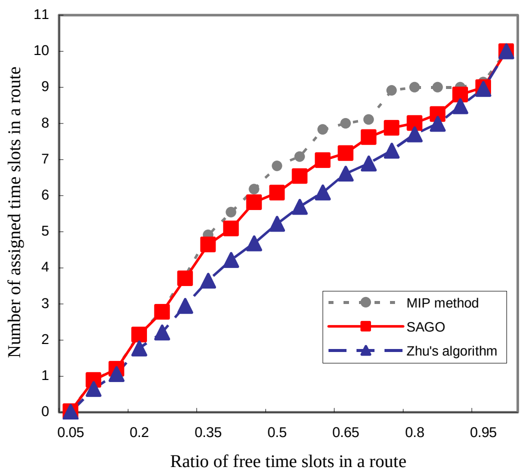

Figure 11. Comparison among three methods
Links: 30 Slots: 30

In addition, SAGO consumes much less time than MIP method. In practice, time slot assignment for a route of 80 links takes 540 seconds by GLPK and only 1 second by our proposal for a computer with 1.5GHz processor and 256MB memory. About the example in Fig.7 of Section III for which no available time slot can be obtained by the conventional method, the time slot assignment can be obtained through the steps in Table III by SAGO.

VI. Conclusion

In this paper, we have studied the time slot assignment for maximum bandwidth of a route in TDMA-based mobile ad hoc networks. We presented an effective time slot assignment algorithm–SAGO, by which time slot assignment is done from a global overview, that is, time

TABLE III
APPLICATION RESULT OF SAGO TO FIG.7

	LinkBW (A,B)	LinkBW (B,C)	LinkBW (C,D)	LinkBW (D,E)	LinkBW (E,F)
Step1				{1}	
Step2				{1}	{4}
Step3			{5}	{1}	{4}
Step4		{2}	{5}	{1}	{4}
Step5	{1}	{2}	{5}	{1}	{4}

slot assignment is based on the usage of global information such as finding of bottleneck of a route, tentative bandwidth evaluation of a route and assignment of time slots in a same link according to their order of free times in the concerned links, i.e. their one-hop and two-hop neighbor links.

We compared our time slot assignment algorithm SAGO with a conventional approximate method and MIP method. By our time slot assignment method, more available bandwidth of a route is obtained than the conventional approximate method and much less time is consumed than MIP method. Furthermore, the bandwidth by our assignment method is in general close to that by MIP method. Thus, our proposed time slot assignment method is concluded as most practical in mobile ad hoc networks.

Our proposal of SAGO can also be applied for the time slot assignment in other slotted wireless ad hoc networks such as CDMA/TDMA[22]. In addition, the results of bandwidth calculation by SAGO can be used for QoS-routing, admission control, load balancing, etc. And it will be a great contribution in end-to-end QoS support research area.

In the future, the proposed time slot assignment will be implemented and integrated with a routing protocol of MANETs.

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