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A Bandwidth Reservation QoS Routing Protocol for Mobile Ad Hoc Networks

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1. Introduction

The advancement in wireless communication and economical, portable computing devices have made mobile computing possible. One research issue that has attracted a lot of attention recently is the design of mobile ad hoc network (MANET). A MANET is one consisting of a set of mobile hosts which can communicate with one another and roam around at their will. No base stations are supported in such an environment. Due to constraints such as battery power, transmission distance, and channel utilization, a mobile host may not be able to communicate directly with all other hosts in a single-hop fashion. In this case, a multi-hop scenario occurs, where packets may need to be relayed by several intermediate hosts before reaching their destinations. Applications of MANETs occur in situations like battlefields and major disaster areas, where networks need to be deployed immediately but base stations or fixed network infrastructures are not available.

Since MANET is characterized by its fast changing topology, extensive research efforts have been devoted to the design of routing protocols for MANETs (Haas & Pearlman, 1998; Johnson et al., 2002; Liao et al., 2001; Perkins & Bhagwat, 1994; Perkins et al., 2002; Royer & Toh, 1999; Wu & Li, 2001). These works only concern with shortest-path routing and the availability of multitude routes in the MANET's dynamically changing environment. So only best-effort data traffic is provided. Issues related to quality-of-service (QoS) requirements, such as delay and bandwidth bounds, are less frequently addressed.

This paper considers the problem of searching for a route of a given bandwidth in a MANET. This problem has been addressed by several works in the literature. References (Chen & Nahrstedt, 1999; Liao et al., 2002) have discussed this problem by assuming quite an ideal model that the bandwidth of a link can be determined independently of its neighboring links. This is untrue if all mobile hosts share a single common channel, or one needs to assume a costly multi-antenna model where a host can send/receive using several antennas simultaneously and independently. A less stronger assumption made in (Lin, 2001; Lin & Liu, 1999) is the CDMA-over-TDMA channel model, where the use of a time slot on a link is only dependent of the status of its one-hop neighboring links. Reference (Stojmenovic et al., 2000) addresses QoS routing with delay and bandwidth constraints, but still no specific channel model is accounted.

In this paper, we assume a simpler TDMA model on a single common channel shared by all hosts. So it is inevitable to take the radio interference problems into consideration. We consider the bandwidth reservation problem in such environment. A route discovery

protocol is proposed, which is able to find a route with a given bandwidth (represented by number of slots). When making reservation, both the hidden-terminal and exposed-terminal problems will be taken into consideration.

The rest of the paper is organized as follows. Section 2 contains backgrounds and preliminaries. Our routing protocol is presented in Section 3. Experimental results are in Section 4. Section 5 concludes this paper.

2. Preliminaries

A MANET is one consisting of a set of mobile hosts which may communicate with one another and roam around at their will. Communication is done through wireless links among mobile hosts by their antennas, but no base stations are supported in such an environment. The MANET distinguishes itself from traditional wireless networks by its dynamic changing topology, no base-station support, and the need of multi-hop communication capability. To support multi-hop communication, a routing protocol is needed to forward data packets.

2.1 QoS transmission in MANET

Guaranteeing QoS is important for networks to support multimedia applications (such as video and audio transmissions). QoS defines nonfunctional characteristics of a system, affecting the perceived quality of the result. For multimedia applications, this may include picture quality, image quality, and speed of response. From technology point of view, QoS characteristics include timeliness (e.g. delay or response time), bandwidth (e.g. bandwidth required or available), and reliability (e.g. normal operation time between failures or down time from failure to restarting normal operation) (Chalmers & Sloman, 1999; Wang & Crowcroft, 1996). Providing QoS is more difficult for MANET due to at least two reasons. First, unlike wired networks, radios have broadcast nature. Thus, each link's bandwidth will be affected by the transmission/receiving activities of its neighboring links. Second, unlike cellular networks, where only one-hop wireless communication is involved, a MANET needs to guarantee QoS on a multi-hop wireless path. Further, mobile hosts may join, leave, and rejoin at any time and any location; existing links may disappear and new links may be formed on-the-fly. All these raise challenges to QoS routing in a MANET.

Issues related to QoS transmission in MANET have received attention recently. In (Sobrinho & Krishnakumar, 1999), this is addressed on the medium access control (MAC) layer, where mobile hosts contend for accessing the common radio channel based on how urgent their data is, and this is determined based on the amount of time that a host has been waiting for the channel to become idle. Once admitted, a host is ensured with high probability to send real-time packets in a collision-free manner. QoS routing is considered in (Chen & Nahrstedt, 1999; Lin, 2001; Lin & Liu, 1999; Stojmenovic et al., 2000). In (Chen & Nahrstedt, 1999), a ticket-based protocol is proposed to support QoS routing. This protocol maintains the end-to-end state information at every node for every possible destination by a distance-vector-like protocol (Perkins & Bhagwat, 1994). A source node s, on requiring a QoS route, can issue a number of probing packets each carrying a ticket. Each probe is in charge of searching for one path, if possible. The basic idea of using tickets is to confine the number of route-searching packets to avoid a blind flooding (flooding in a MANET is very costly, according to (Ni et al., 1999)). Each probe, on reaching an intermediate node, should choose one outgoing path that satisfies the QoS requirements. However, this paper assumes that the

bandwidth of a link can be determined independently of its neighboring links. The is quite a strong assumption, because a costly multi-antenna model may be needed. Otherwise, such an assumption is generally untrue because neighboring mobile hosts sharing a common channel will interference with each other. In (Lin, 2001; Lin & Liu, 1999), how to calculate the bandwidth of a routing path in a MANET is addressed. A CDMA-over-TDMA channel model is assumed. The code used by a host should be different from that used by any of its two-hop neighbors. So a code assignment protocol should be supported (this can be regarded as an independent problem; references can be found in (Bertossi & Bonuccelli, 1995; Garcia-Luna-Aceves & Raju, 1997; Ju & Li, 1999)). The bandwidth requirement is realized by reserving time slots on links. Based on such assumption, this paper shows how to allocate time slots on each link of a path such that no two adjacent links share a common time slot. Reference (Stojmenovic, 2000) addresses QoS routing with delay and bandwidth constraints. It suggests that the depth-first search be used to find routes. However, no specific channel model is accounted.

2.2 System model and challenges

This paper is concerned with QoS routing in a MANET. Different from the above referenced works, we assume a simpler (and perhaps more realistic) TDMA-based channel model. One single common channel is assumed to be shared by all hosts in the MANET. The channel is time-framed. Each frame is divided into a control phase and a data phase, as shown in Fig. 1. The former supports various kinds of control functions, such as frame synchronization, call setup, call maintenance, and time slot reservation for QoS routing. The latter consists of s time slots, indexed from 1 to s, each being able to carry one data packet, where s is a predefined integer. This model may be emulated by wireless LAN cards which follow the IEEE 802.11 standard (IEEE, 1997).
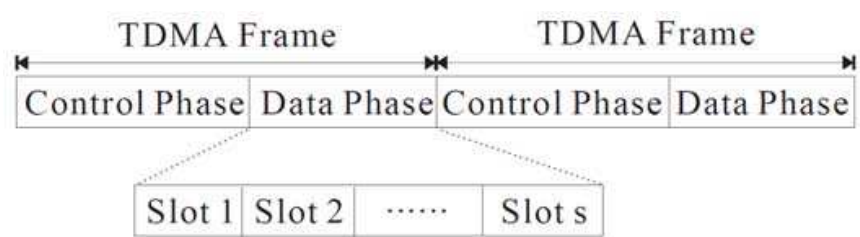

Fig. 1. The TDMA frame structure.

Because an antenna can not send and receive at the same time, bandwidth calculation in a multi-hop route is a non-trivial problem. Take the path from A to C in Fig. 2(a) as an example, where the white slots associated with each host are free and the gray slots are busy. Matching the free slots between hosts, we obtain five common free time slots {1, 2, 3, 4, 5} between A and B and four common free time slots {3, 4, 5, 6} between B and C. One may naively think that the path bandwidth from A to C is four (= min { 4, 5 }). Unfortunately, this is not true. As shown in Fig. 2(b), if we reserve slots {1, 2, 3} for A to transmit and slots {4, 5, 6} for B to transmit, the path bandwidth is only three. In fact, it is not hard to see that it is impossible to further increase the path bandwidth in this example. Even worse, as shown in Fig. 2(c), if one reserves slots {3, 4} for A to transmit and slots {5, 6} for B to transmit, the path bandwidth will degrade to two, and the situation cannot be improved, unless we change the assignment for A.
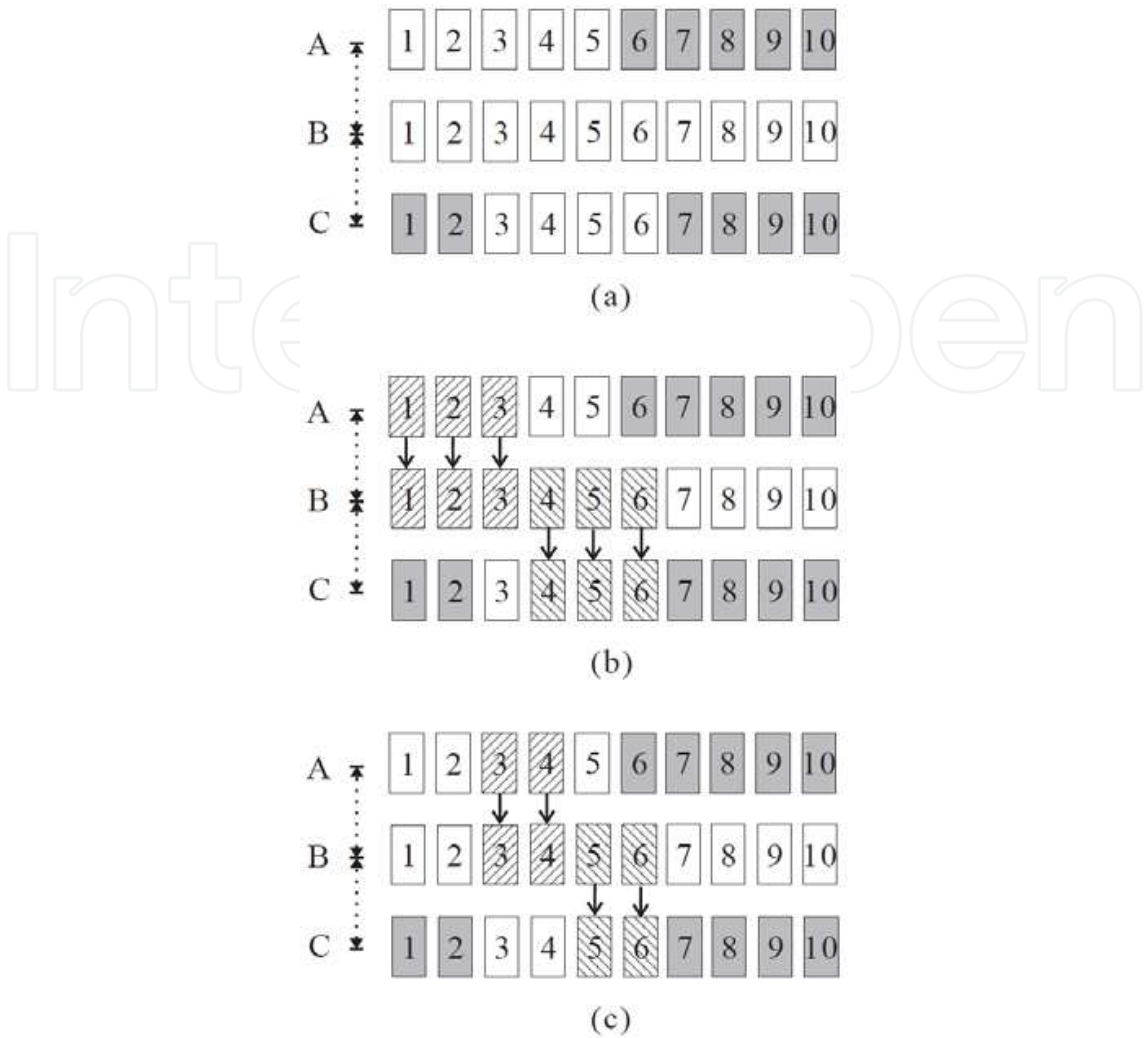
Fig. 2. The bandwidth calculation problem under the TDMA model: (a) free and busy time slots, (b) an assignment with bandwidth = 3 slots from *A* to *C*, and (c) an assignment with bandwidth = 2 from *A* to *C*.

The above discussion has already been simplified by purposely ignoring the transmission and reception activities of individual mobile hosts. At this point, we'd like to recall the hidden-terminal and exposed-terminal problems, which are well-known problems in the literature of radio-based communication. Consider the scenario in Fig. 3, where the status of *A*, *B*, and *C* is the same as the above example. Suppose there is another pair, *D* and *E*, who are currently using slot 2 to communicate. Then two cases will occur. If *D* is a receiver on slot 2, *A* will not be allowed to send on slot 2 because otherwise collision will occur at *D*. This is the hidden-terminal problem. So in the example of Fig. 2, the common free time slots between *A* and *B* should be reduced to {1, 3, 4, 5}. Then the case in Fig. 2(b) will not hold anymore, and the path bandwidth from *A* to *C* has to downgrade to 2 slots. On the contrary, if *D* is a sender on slot 2, *A* will still be allowed to send on slot 2, because this is an exposed-terminal problem. Then the common free time slots between *A* and *B* (and thus the path bandwidth) remain the same.

While the above examples already show the complication in the bandwidth reservation problem, we'd like to comment on the data structure used above. From the discussion, we

see that simply indicating a time slot as busy or free is insufficient to resolve the hidden- and exposed-terminal problems. For the busy case, we need to tell whether the host is sending or receiving in this slot. This observation motivates our design in the next section.
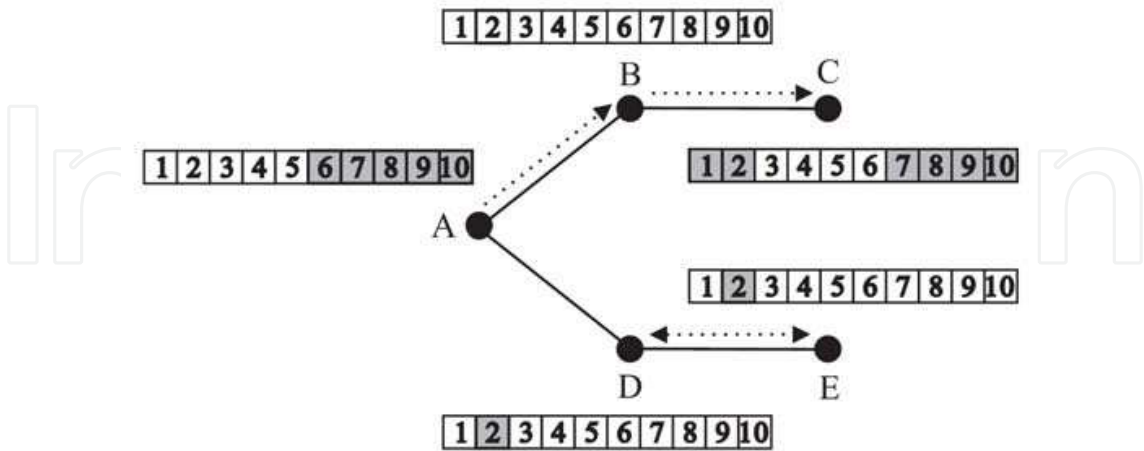

Fig. 3. Example of how bandwidth calculation is interfered by the hidden- and exposed-terminal problem.

3. QoS routing protocol

3.1 Basic idea

Our routing protocol is an on-demand one, so route search is done only when necessary. (The contrary is proactive, which is generally regarded to be more costly.) It is based on source routing, and works similar to the DSR protocol (Johnson et al., 2001) on disseminating route-searching packets, but we need to carefully calculate the bandwidth of each route being searched.

A source host S, on requiring a route to a destination D with bandwidth b, will issue through broadcast a QoS route request packet $QREQ(…, b, PATH, NH)$ to its neighbors. The field $PATH$ provides the important information to keep track of the partial route and time slots that the $QREQ$ packet has discovered so far. The NH is a list of hosts, each of which may be used as the next hop to extend $PATH$ with one more hop. Any host x listed in NH hearing this $QREQ$ for the first time may rebroadcast this packet, if it has sufficient collision-free time slots (here the route cache design may be raised to reduce the flooding cost; however, we deal this as an independent issue and refer the reader to the literature (Marina & Das, 2001; Perkins et al., 2002). In x's rebroadcast, proper information will be added to $PATH$ and NH.

When D receives the $QREQ$ packet, it can reply a QoS route reply packet $QREQ(…, PATH)$ destined to the source S. This packet will be routed, through unicast, along the reverse direction of $PATH$, and on its way back reserve proper time slots at intermediate hosts according to the content in $PATH$. Our protocol relies on the following lemma to choose time slots in a host.

Lemma 1: A time slot t can be used by a host X to send to another host Y without causing collision if the following conditions are all satisfied:

1. Slot t is not yet scheduled to send or receive in neither X nor Y.
2. For any 1-hop neighbor Z of X, slot t is not scheduled to receive in Z.
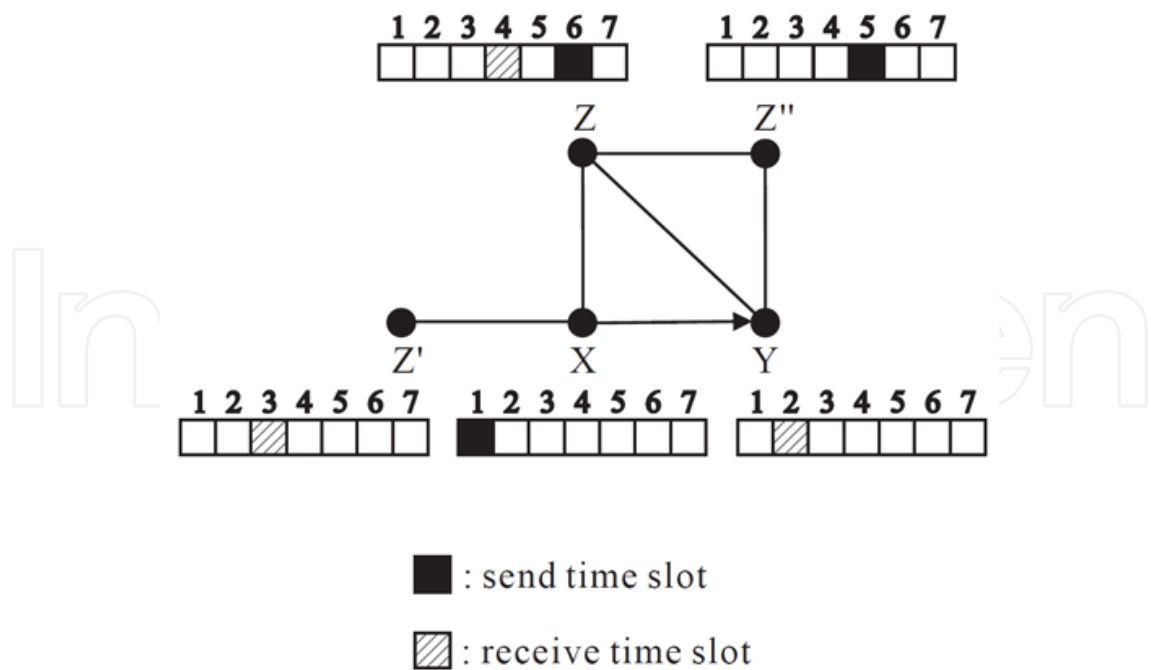3. For any 1-hop neighbor Z of Y, slot t is not scheduled to send in Z.

Fig. 4. An example of Lemma 1.

For example, in Fig. 4, a host X needs a time slot to transmit to a host Y. First, slots 1 and 2 can not be considered because slot 1 is used by X to send and slot 2 is used by Y to receive. Second, slots 3 and 4 can not be considered because they will cause collision at Z and Z'. Third, slots 5 and 6 can not be considered because Z and Z'' are sending on these slots. So we conclude that only slot 7 can be used.

3.2 Data structures

We will index hosts by numbers 1, 2, … , n, and time slots by 1, 2, …, s. Each host x will maintain three tables as follows.

- $ST_x[1..n, 1..s]$: the *send table* of x, which records on which time slots a host which is within 2 hops from x will have sending activities. Specifically, $ST_x[i, j]= 1$ if slot j of host i has been reserved for sending; otherwise, $ST_x[i, j]=0$.

- $RT_x[1..n, 1..s]$: the *receive table* of x, which records on which time slots a host which is within 2 hops from x will have receiving activities. Specifically, $RT_x[i, j]= 1$ if slot j of host i has been reserved for receiving; otherwise, $RT_x[i, j]= 0$.

- $H_x[1..n, 1..n]$: the *hop-count matrix* of x, which is to keep track of the mutual distances between hosts in x's neighborhood. Specifically, for each host i that is within 1 hop from x, $H_x[i, j] = 1$ if host j is within 1 hop from i; otherwise, $H_x[i, j] = \infty$.

In Fig. 5, host A is sending to E on the path $A \rightarrow B \rightarrow C \rightarrow D \rightarrow E$ of bandwidth of 2 slots. Slots {1, 2}, {3, 4}, {5, 6}, and {7, 8} are used by A, B, C, D to send, respectively. They are reflected on each host's ST and RT tables. Note that the rows $ST_x[x, j]$ and $RT_x[x, j]$ indicate the sending and receiving activities of host x itself. In order to create these data structures, a host needs to periodically broadcast its own status to its 2-hop neighbors.

To search for a QoS route, we mainly use the packet $QREQ(S, D, id, b, x, PATH, NH)$, whose parameters are defined as follows.
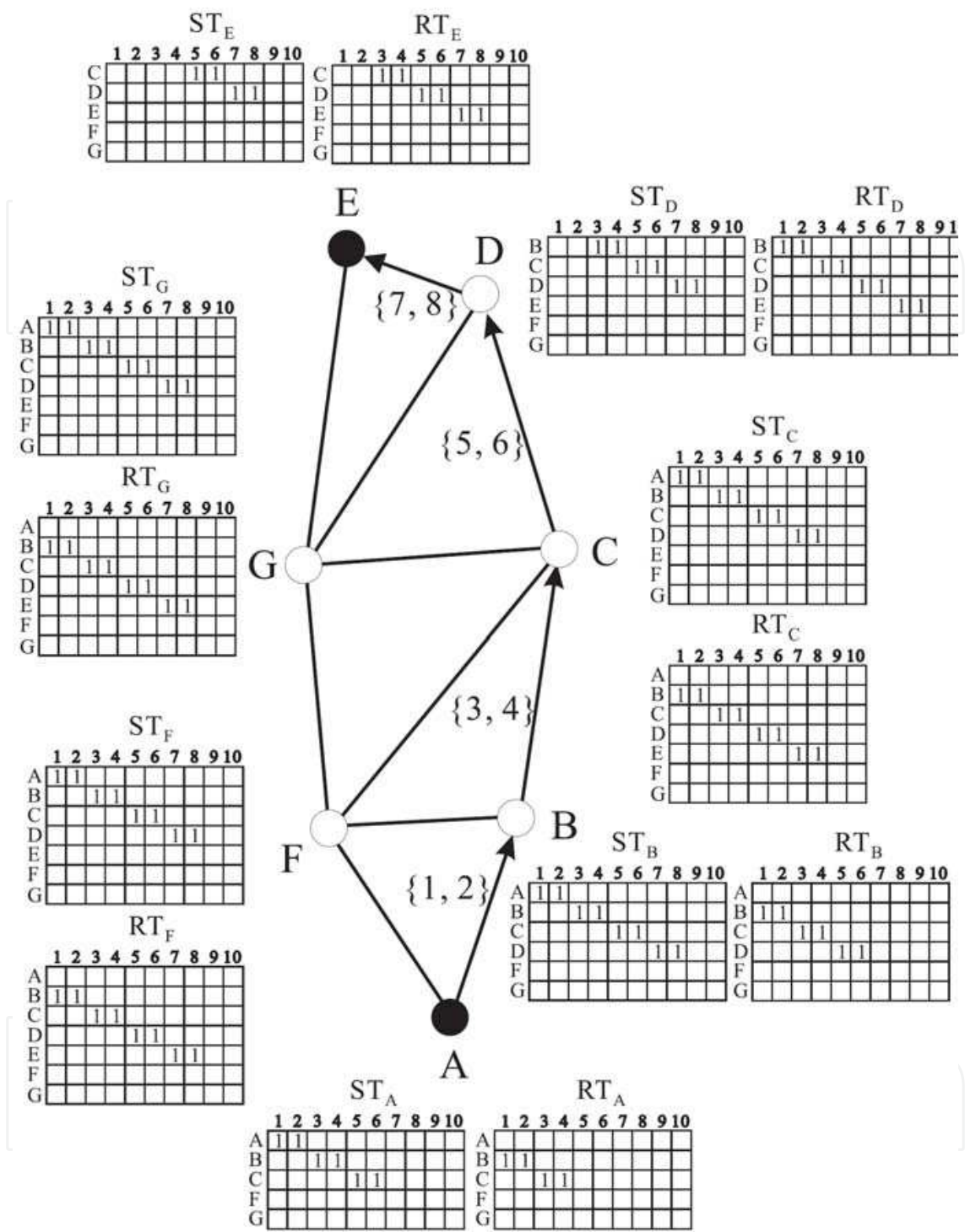
- S: the source host.
- D: the destination host.

Fig. 5. Example of time slot tables ST and RT.

- *id*: an identity which is unique to each route-searching request issued by *S*. So the triplet (*S*, *D*, *id*) can be used to detect duplicate *QREQ* to avoid endless looping.
- *b*: the bandwidth requirement, represented by an integer number of slots.
- *x*: the host currently relaying the *QREQ* packet.
- *PATH*: the partial path, together with the available time slots, that has been discovered so far. It has the format $((h_1, l_1), (h_2, l_2), \ldots, (h_k, l_k))$. Each h_i, $i=1..k$, is a host identity, so the

sequence h_1, h_2, ..., h_k, x represents the current partial path. Each l_i contains a total of b time slots that are found to be available for h_i to transmit to h_{i+1}, with the exception that h_k's intending receiver is host x.

- *NH*: a list next-hop hosts of the format $((h_1', l_1'), (h_2', l_2'), ...)$. Each host h_i' has potential to serve as the next hop of host x to extend the current partial path (so the new path will be h_1, h_2, ..., h_k, x, h_i'). However, this will depend on whether h_i' has sufficient time slots or not (this will become clear in the protocol). The corresponding parameter l_i' contains b time slots that can be used by x to transmit to h_i' without collision.

When a route is found, we need to initiate from the destination D a packet *QREP*(*S*, *D*, *id*, *PATH*) to the source S. This packet will travel on the reverse direction of *PATH* and reserve time slots, as discovered, on the path. These parameters carry the same meanings as above.

3.3 Protocol details

Now suppose a host y receiving a broadcasting packet *QREQ*(*S*, *D*, *id*, *b*, *x*, *PATH*, *NH*) initiated by a neighboring host x. If the same route request (uniquely identified by (*S*, *D*, *id*)) has not be heard by y before, it will perform the following steps:

A1. **if** (y is not a host listed in *NH*) **then**

   exit this procedure.

   else

   Let (h_i', l_i') be the entry in *NH* such that $h_i' = y$.

   Construct a list   *PATH_temp* = *PATH* | (x, l_i'), where | means list concatenation.

   end if.

A2. Construct two temporary tables, *ST_temp*[1..*n*, 1..*s*] and *RT_temp*[1..*n*, 1..*s*], as follows.

i.   Copy all entries in ST_y[1..*n*, 1..*s*] into *ST_temp*[1..*n*, 1..*s*], and similarly copy all entries in RT_y[1..*n*, 1..*s*] into *RT_temp*[1..*n*, 1..*s*].

ii. Let *PATH* = $((h_1, l_1), (h_2, l_2), \cdots, (h_k, l_k))$.   For each $i = 1..k-1$, assign *ST_temp*$[h_i, t]$ = 1 and assign *RT_temp*$[h_{i+1}, t]$ = 1 for every time slot t in the list l_i. Assign *ST_temp*$[h_k, t]$ = 1 and assign *RT_temp*$[x, t]$ = 1 for every time slot t in the list l_k.

iii. Recall l_i' (the slots for x to send to y). Let *ST_temp*$[x, t]$ = 1 and *RT_temp*$[y, t]$ = 1 for every time slot t in the list l_i'.

These temporary tables, *ST_temp* and *RT_temp*, are obtained from *ST*, *RT*, *PATH*, and *NH*. This is because we are in the probing stage, but *ST* and *RT* only contain slot status already confirmed. The information in *PATH* and *NH* has to be introduced into these temporary tables.

A3. Let *NH_temp* = ϕ (i.e., an empty list).

   for each 1-hop neighbor z of y **do**

   L = select_slot(y, z, b, *ST_temp*, *RT_temp*)

   if $L \neq \phi$ **then**

   NH_temp = *NH_temp* | (z, L)

   end if

   end for

The above step calls for a procedure *select_slot()*, which will return, if possible, b available slots that can be used by y to send to z (the details will be shown later). If the above loop can find at least one host to extend the current path, the *QREQ* will be rebroadcast, as shown below.

A4. **if** $NH\_temp \neq \phi$ **then**
     broadcast $QREQ(S, D, id, b, y, PATH\_temp, NH\_temp)$
   end if

The source host S will initiate the $QREQ$. It can be regarded as a special case of intermediate hosts, and can perform similarly to the above steps by replacing host y with S. We only summarize the modifications required for S. First, S has not $PATH$ and NH. So in S1, the checking of NH is unnecessary. We can simply set $PATH\_temp =\phi$. Also, step A2 can be simplified to only executing step i. The other steps remain the same.

When the destination D receives packet $QREQ(S, D, id, b, x, PATH, NH)$, a satisfactory path has been formed. D can accept the first $QREQ$ received, or choose based on other policy. Then following steps will be executed.

B1. Let (h_i', l_i') be the entry in NH such that $h_i' = D$.
B2. $PATH\_temp = PATH \mid (x, l_i')$.
B3. Send $QREP(S, D, id, PATH\_temp)$ to S.

Note that the $QREP$ packet will travel in the reverse direction of $PATH$ through unicast. Each intermediate host should relay this packet. In addition, proper sending and receiving activities should be recorded in their sending and receiving tables. Specifically, let the whole path be $PATH = ((h_1, l_1), (h_2, l_2), \ldots, (h_k, l_k))$. For each intermediate host $x = h_i$, the following steps should be conducted.

C1. **for** $j = i - 2$ **to** $i + 2$ **do**
       Let $ST_x[h_j, t]=1$ for each time slot t in l_j.
    end for

C2. **for** $j = i - 2$ **to** $i + 2$ **do**
       Let $RT_x[h_j, t]=1$ for each time slot t in l_{j-1}.
     end for

3.4 Time slot selection

The procedure $select\_slot(y, z, b, ST\_temp, RT\_temp)$ is for host y to choose b free time slots to send to z. It mainly relies on Lemma 1 to do the selection. Specifically, for each time slot i, $1 \leq i \leq s$, we check the following conditions D1, D2, and D3. If all conditions hold, slot i is a free slot that can be used by y to send to z.

D1. $(ST\_temp[y, i]=0) \wedge (RT\_temp[y, i]=0) \wedge (ST\_temp[z, i]=0) \wedge (RT\_temp[z, i]=0)$.
D2. $\forall w : (H_y[y, w] = 1) \Rightarrow RT\_temp[w, i]=0$.
D3. $\forall w : (H_y[z, w] = 1) \Rightarrow ST\_temp[w, i]=0$.

To respond the procedure call in A3, if there are at least b time slots satisfying the above conditions, we should return a list of b free slots to the caller; otherwise, an empty list ϕ should be returned. When there are more than b time slots available, we can further choose slots based on some priority. The basic idea is to increase channel reuse (which is generally favorable in almost all kinds of wireless communications). Those slots which have the exposed-terminal problem can be chosen with higher priority. To reflect this, we can give a legal time slot i a higher priority such that $ST\_temp[w, i]=1$ for some neighbor w of x.

$$\blacksquare = (B, G, 1, 2, B, PATH=\emptyset,$$
$$NH=((A, \{7, 8\}), (C, \{9, 10\}), (F, \{7, 8\})))$$

$$\text{▥} = (B, G, 1, 2, F, PATH=(B, \{7, 8\}),$$
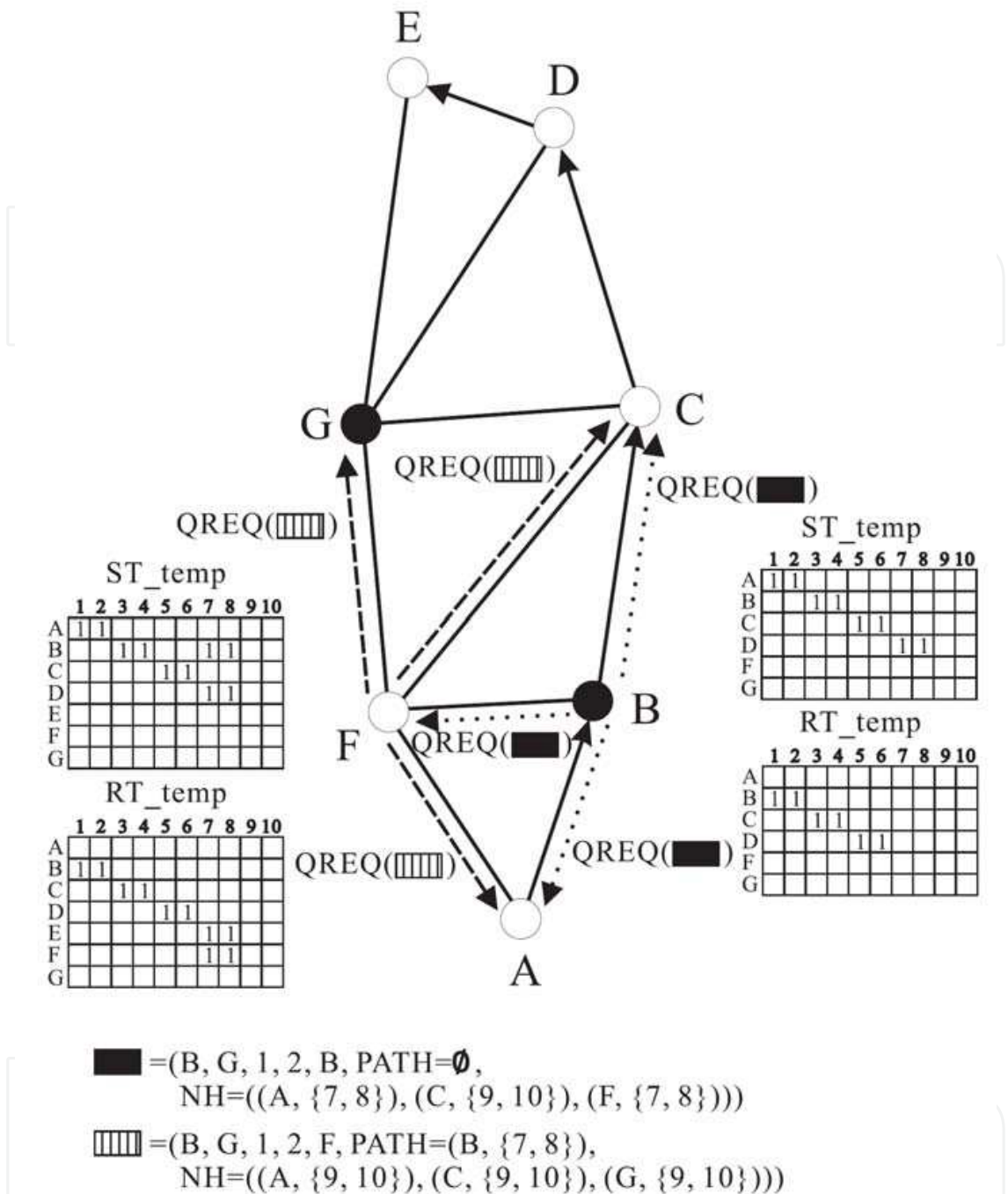$$NH=((A, \{9, 10\}), (C, \{9, 10\}), (G, \{9, 10\})))$$

Fig. 6. An example of QREQ propagation in our protocal.

3.5 Example

Following the example in Fig. 5, we show in Fig. 6 how *B* searches for a route of bandwidth 2 slots to *G*. Since *B* is the source, the *ST_temp* and *RT_temp* are equal to ST_B and RT_B, respectively. Each of hosts *A*, *C*, and *F* can serve as the next hop by using slots {7, 8}, {9, 10}, and {7, 8}, respectively, as reflected in the packet content. We also show *F*'s *ST_temp* and *RT_temp* when searching for the next host. Hosts that can serve as the next hop of *F* are *A*, *C*, and *G*. The *QREQ* packets sent by other hosts are not shown for clarity. Finally, when *G* receives *F*'s *QREQ*, it may reply a *QREP*(*B*, *G*, 1, (*B*, {7, 8}), (*F*, {9, 10})) to *B*.

4. Experimental results

We have developed a simulator to evaluate the performance of the proposed bandwidth reservation scheme. A MANET in a $1000m \times 1000m$ area with 20 ~ 70 mobile hosts was simulated. Each mobile host had the same transmission range of 300 meters. Hosts might roam around continuously for 5 seconds, and then have a pose time from 0 ~ 8 seconds. The roaming speed is 0 ~ 20 m/s, with a roaming direction which was randomly chosen in every second. A data transmission rate of 11 Mbit/s was used. Each time frame had 16 ~ 32 time slots, with 5 ms for each time slot. Traffic was generated from randomly chosen source-destination pairs with bandwidth requirement of 1, 2, or 4 slots (denoted as QoS1, QoS2, and QoS4, respectively). New calls arrived with an exponential distribution of mean rate 1/12000 ~ 1/500 per ms. Each call had duration of 180 sec. Since our goal was to observe multi-hop communication, we impose a condition that each source-destination pair must be distanced by at least two hops. The total simulation time was 1000 sec.

We make observations from several aspects.

A) Network throughput: When calculating throughput, we only count packets that successfully arrive at their destinations. In Fig. 7, we show the network throughput under various loads, where load is defined to be the bandwidth requirement (which are 1, 2, and 4 for QoS1, QoS2, and QoS4, respectively) times the corresponding call arrival rate. Among the simulated ranges, the throughputs all increase linearly with respect to loads for all QoS types. This indicates that QoS routing can be supported quite well by MANET based on our protocol. As comparing different bandwidth requirements, QoS4 performs slightly worse than QoS1 and QoS2. The reason will be elaborated below.

To understand the above scenarios, we further investigate the call success rate (the probability to accept a new call) under the same inputs. The results are in Fig. 8 .When the traffic load increases, the success rates decrease for all QoS types. The success rate of QoS1 is the largest, which is followed by QoS2, and then QoS4. This is reasonable because larger bandwidth requirements are more difficult to satisfy.

Next, we investigate the average number of hops for all source-destination pairs under different bandwidth requirements. The result is in Fig. 9. We see that QoS4 routes are the shortest in all ranges. One interesting thing is that when the traffic load is higher than 1/1000, the lengths of QoS1 routes will start to increase, while on the contrary those of QoS4 routes will drop significantly. The reason is that it is less likely to find satisfactory, but long QoS4 routes under heavy load. But for QoS1 routes, the chances are actually higher. This is why QoS1 gives the best network throughput.

B) Effect of host density: In this experiment, we vary the total number of hosts. Since the physical area is fixed, this actually reflects the host density (or crowdedness of the environment). The result is in Fig. 10. First, we observe that the network throughput will improve as the network is denser under all QoS types. This is perhaps due to richer choices of routing paths. Second, there will be larger performance gaps between low QoS routes (such as 1 and 2) and high QoS routes (such as 4). So higher host density is more beneficial to low-bandwidth routes.

C) Effect of host mobility: In Fig. 11, we show the throughput under various host mobility. We see that throughput is very sensitive to mobility in all QoS types. In our simulation, whenever a route is broken, an error message will be sent to the source host. Before the source host knows this fact, all packets already sent will still consume time slots without contributing to the real throughput. Furthermore, before a new route is discovered, some time slots will be idle. This is why we see significant drop on throughput as mobility increases, which also indicates a challenging problem deserving further research.

D) Effect of frame length: In Fig. 12, we show the network throughput when a time frame has 16, 24, and 32 time slots. Longer frame length will be more beneficial to requests with higher QoS requirements. This is reasonable because requests with larger QoS requirements get rejected with higher probability as the frame length is shorter.
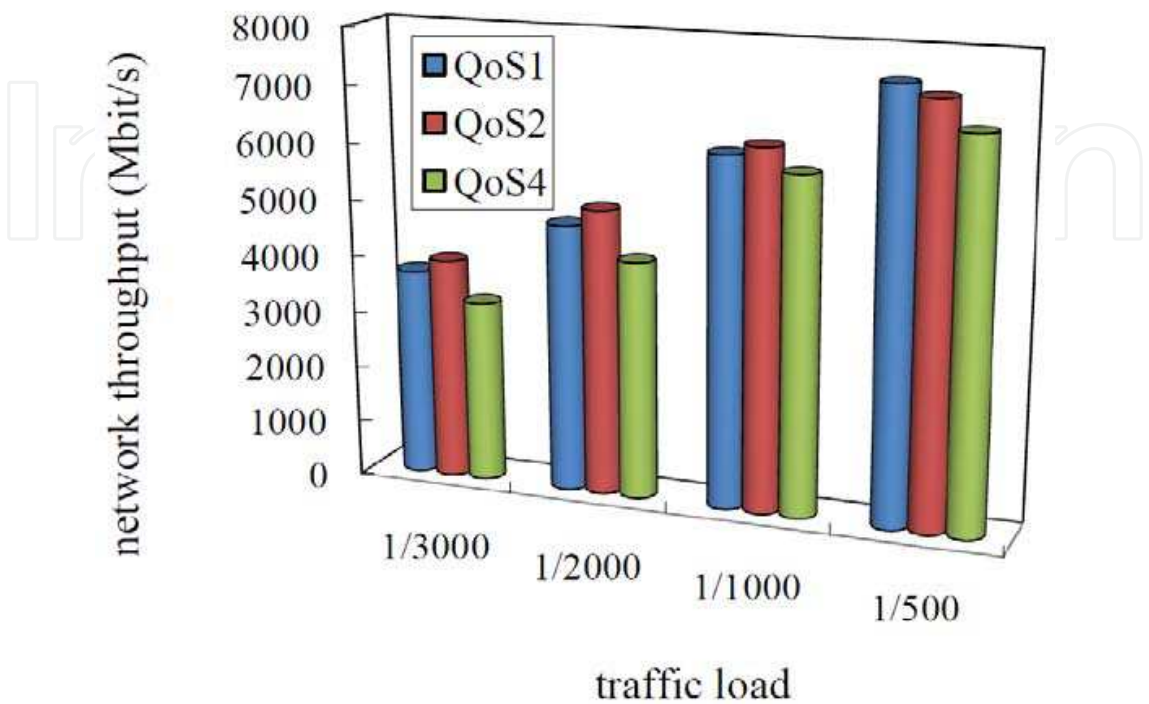

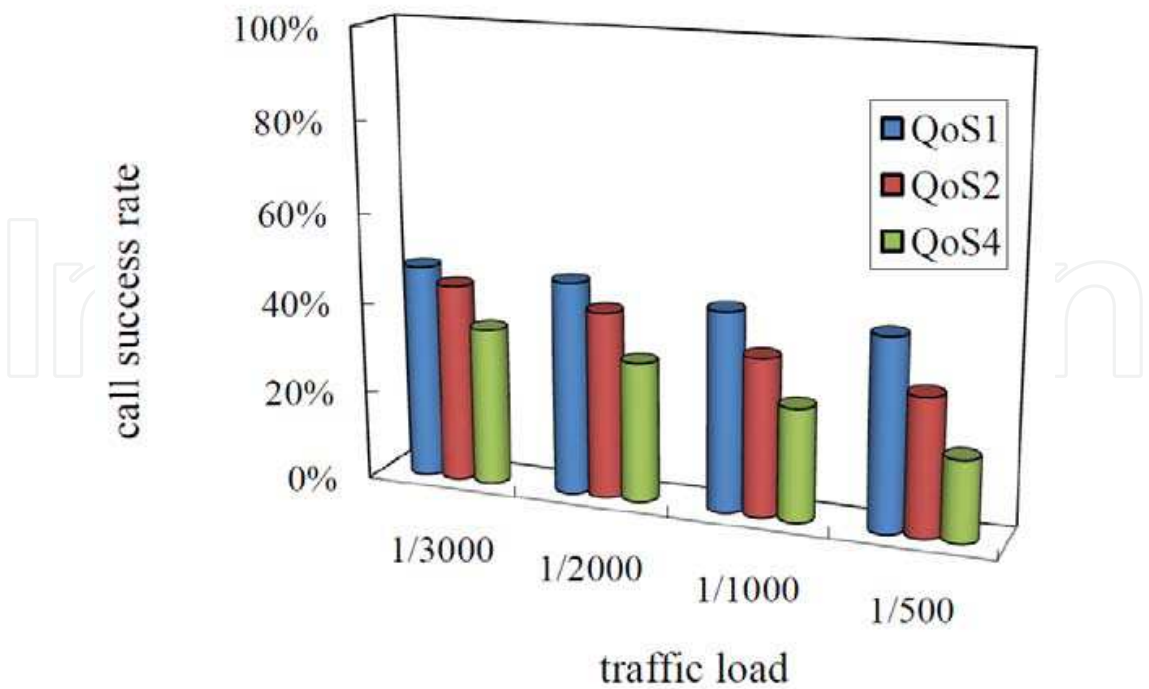Fig. 7. Network throughput vs. traffic load (= QoS requirement times call arrival rate), where number of hosts=30, number of time slots=16, pose time=0, and mobility=4m/s.

Fig. 8. Call success rate vs. traffic load, where number of hosts=30, number of time slots=16, pose time=0, and mobility=4m/s.
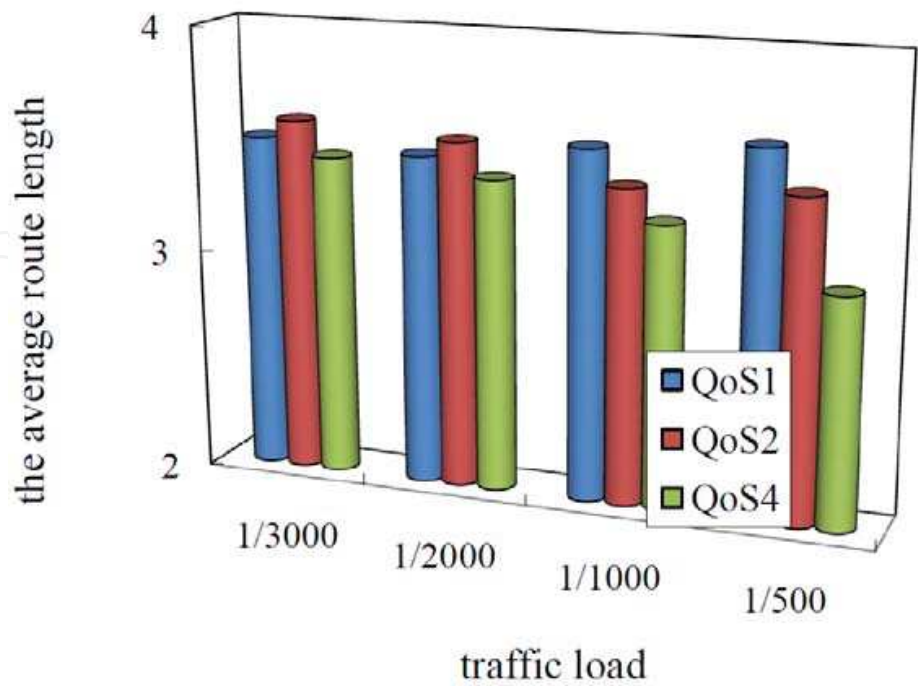
Fig. 9. The average route length v.s. traffic load, where number of hosts=30, number of time slots=16, pose time=0, and mobility=4m/s.
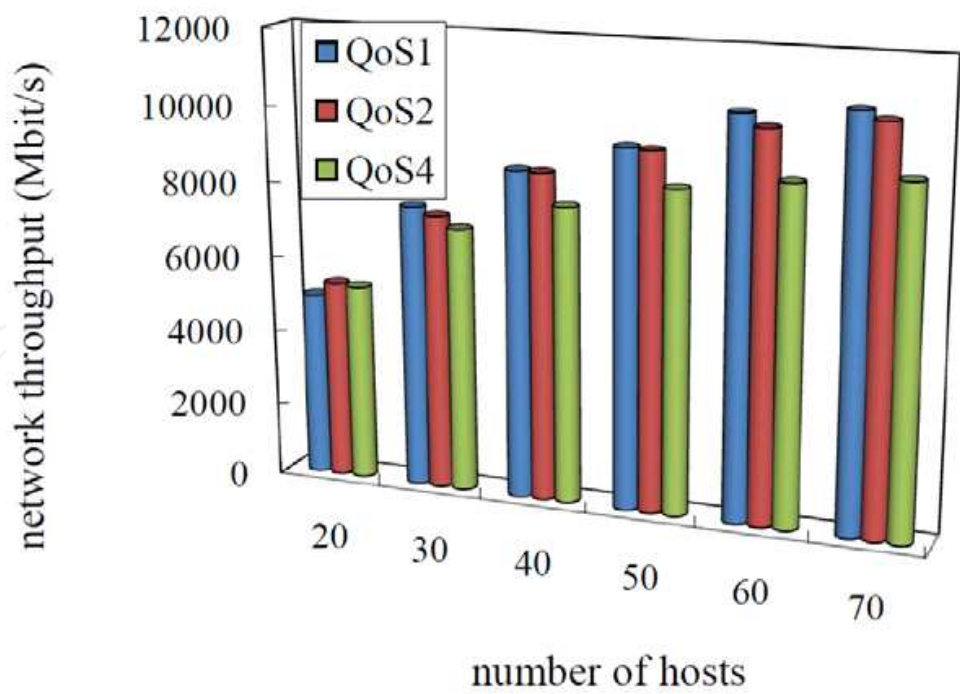
Fig. 10. Network throughput v.s. host density, where traffic load=1/500, number of time slots=16, pose time=0, and mobility=4m/s.
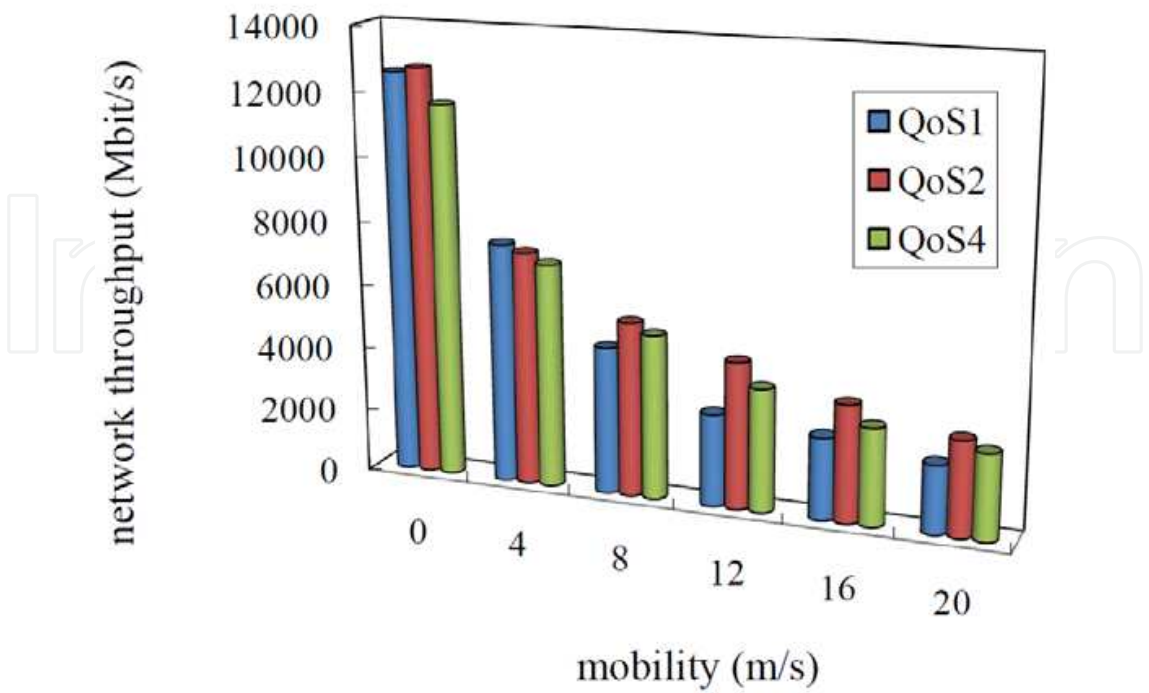
Fig. 11. Network throughput v.s. mobility, where number of hosts=30, number of time slots=16, pose time=0, and traffic load=1/500.
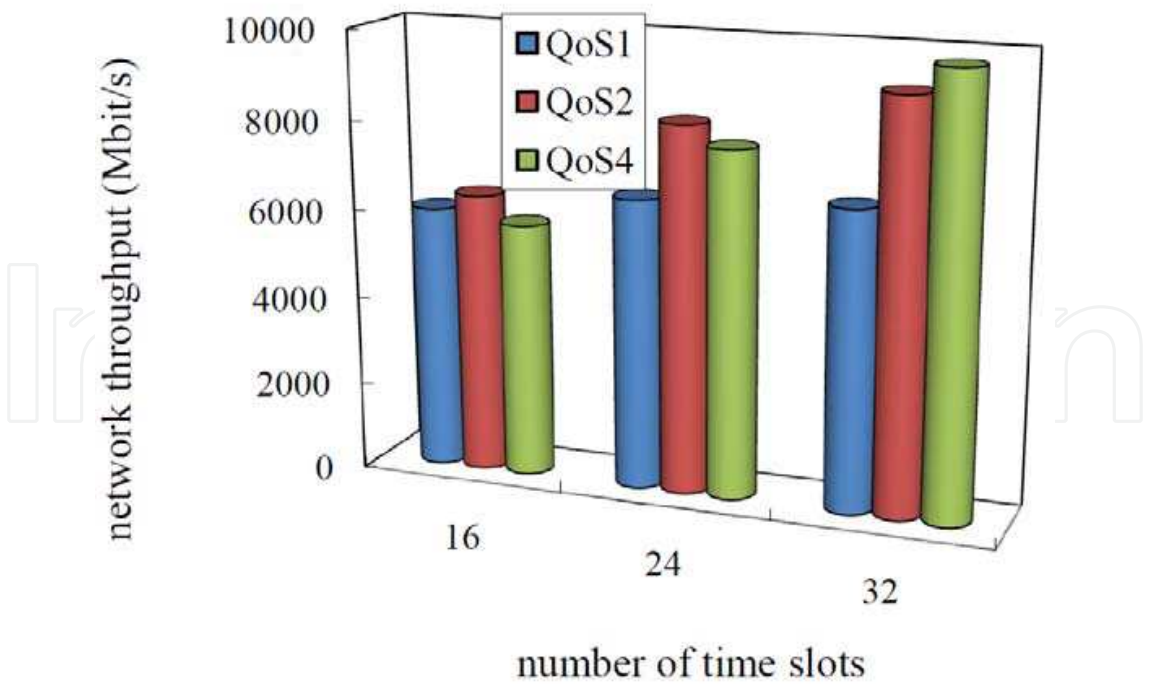

Fig. 12. Network throughput v.s. frame length, where number of hosts=30, pose time=0, mobility=4m/s, and traffic load=1/1000.
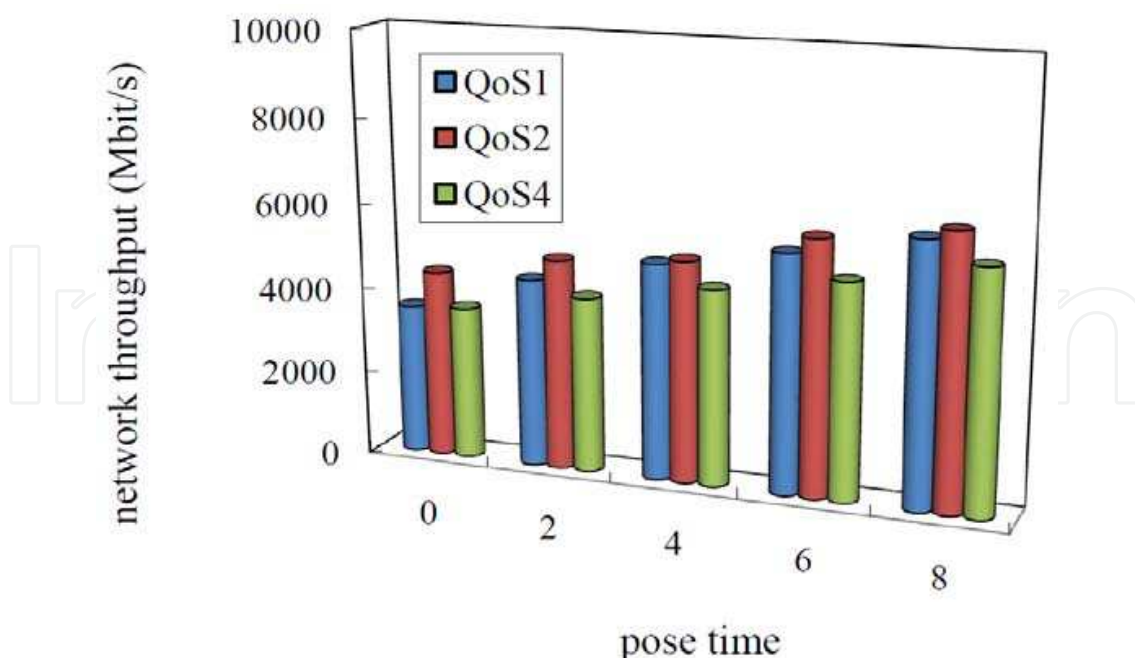
Fig. 13. Network throughput v.s. pose time, where number of hosts=30, number of time slots=16, mobility=8m/s, and traffic load=1/1000.

E) Effect of pose time: Recall that we adopt a roaming model that a host will continue move for 5 seconds, and then pose for 0 to 8 seconds. In Fig. 13, we show the network throughput under various pose times. Longer pose time is beneficial for all types of QoS routes, which is reasonable because the probability of route broken will drop.

5. Conclusions

In this paper, we have proposed a TDMA-based bandwidth reservation protocol for QoS routing in a MANET. Most existing MANET routing protocols do not guarantee bandwidth when searching for routes. Few works have considered the same QoS routing problem, but are under a stronger multi-antenna model or a less stronger CDMA-over-TDMA channel model. Our protocol assumes a simpler (and perhaps more practical) TDMA-based channel model. One single common channel is assumed to be shared by all hosts in the MANET. Hence the result may be applied immediately to current wireless LAN cards. One interesting point is that our protocol can take into account the difficult hidden-terminal and exposed-terminal problems when establishing a route. So more accurate route bandwidth can be calculated and the precious wireless bandwidth can be better utilized. We are currently trying to further optimize the bandwidth utilization from a global view.

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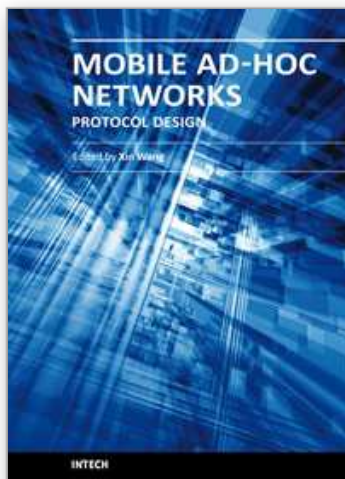
Mobile Ad-Hoc Networks: Protocol Design

Edited by Prof. Xin Wang

Being infrastructure-less and without central administration control, wireless ad-hoc networking is playing a more and more important role in extending the coverage of traditional wireless infrastructure (cellular networks, wireless LAN, etc). This book includes state-of-the-art techniques and solutions for wireless ad-hoc networks. It focuses on the following topics in ad-hoc networks: quality-of-service and video communication, routing protocol and cross-layer design. A few interesting problems about security and delay-tolerant networks are also discussed. This book is targeted to provide network engineers and researchers with design guidelines for large scale wireless ad hoc networks.

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Wen-Hwa Liao (2011). A Bandwidth Reservation QoS Routing Protocol for Mobile Ad Hoc Networks, Mobile Ad-Hoc Networks: Protocol Design, Prof. Xin Wang (Ed.), ISBN: 978-953-307-402-3, InTech, Available from: http://www.intechopen.com/books/mobile-ad-hoc-networks-protocol-design/a-bandwidth-reservation-qos-routing-protocol-for-mobile-ad-hoc-networks

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