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A Shoelace-Based QoS Routing Protocol for Mobile Ad Hoc Networks Using Directional Antenna

Yuh-Shyan Chen · Chih-Shun Hsu · Shin-Jr Jan

Abstract In this paper, we propose a new quality-of-service (QoS) routing protocol for mobile ad hoc network (MANET) using directional antennas. The proposed scheme offers a bandwidth-based routing protocol for QoS support in MANET using the concept of multi-path. Our MAC sub-layer adopts the CDMA-over-TDMA channel model. The on-demand QoS routing protocol calculates the end-to-end bandwidth and allocates bandwidth from the source node to the destination node. The paths are combined with multiple cross links, called shoelace, when the network bandwidth is strictly limited. Due to the property of the directional antenna, these cross links can transmit data simultaneously without any data interference. We develop a shoelace-based on-demand QoS routing protocol by identifying shoelaces in a MANET so as to construct a QoS route, which satisfied the bandwidth requirement, more easily. The shoelace-based route from the source to the destination is a route whose sub-path is constructed by shoelace structure. With the identified shoelaces, our shoelace-based scheme offers a higher success rate to construct a QoS route. Finally, simulation results demonstrate that the proposed routing protocol outperform existing QoS routing protocols in terms of success rate, throughput, and average latency.

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1 Introduction

A mobile ad hoc network is a group of mobile nodes that dynamically forms a network without the aid of any existing network infrastructure. Each node can self-organize and communicate with each other by a multi-hop mechanism. In a MANET, the host mobility can cause frequent unpredictable topology changes, and thus the design of a QoS routing protocol in MANETs is more complicated than that of the traditional networks. Recently, some works have intensively studied QoS issues in MANETs. Several QoS multicast protocols for MANETs have been proposed, such as [3–5,16]. However, these QoS multicast protocols typically assume the usage of omni-directional antennas by all the nodes. With omni-directional transmission, the distribution of energy in all directions other than just the intended direction generates unnecessary interference to other nodes thereby considerably reduces network capacity. Recently, some routing protocols for MANETs with directional antennas have been proposed, such as [1,8,10,13,14,18,20,22,23,25]. With directional transmission, both the transmission range and spatial reuse can be substantially enhanced by concentrating nodes' transmitted energy only towards their destination's direction, thereby achieving higher success rate. The use of directional antenna in MANETs can largely reduce the radio interference, thereby improving the utilization of wireless medium and consequently the network performance [7,11]. Unfortunately, directional transmissions increase the hidden terminal problem, the problem of deafness and the problem of the determination of neighbors' location. These problems are researched and discussed in [2,6,12,21]. Choudhury and Vaidya [6] have proposed the ToneDMAC to address the deafness problem; Korakis et al. [12] have used circular directional RTS to determine neighbors' location. However, these routing protocols for ad hoc networks with directional antennas do not provide the QoS function.

In this paper, we propose a shoelace-based QoS routing protocol using directional antennas in MANETs. The CDMA-over-TDMA channel model is adopted as our MAC sub-layer model. This channel model is also adopted by several QoS routing protocols for MANETs [3,5,16,17], where the use of a time slot on a link only depends on the status of its one-hop neighboring links. Based on this channel model, this paper constructs a shoelace-based routing protocol using directional antennas to achieve the QoS requirement. This paper provides an on-demand dynamic routing path according to the network bandwidth. The shoelace-based route is a uni-path route if the network bandwidth is sufficient and is a multi-path route if the network bandwidth is insufficient. The main features of our shoelace-based protocol are summarized as follows: (1) the shoelace-based protocol produces cross link which can simultaneously transmit data without any interference; (2) the shoelace-based protocol employs the concept of multi-path to achieve QoS requirement when the network bandwidth is strictly limited; (3) the shoelace-based protocol offers a higher success rate to achieve the QoS requirement. In particular, the proposed scheme can be directly applied to most of the existing protocols with directional antennas.

The rest of this paper is organized as follows. Section 2 discusses related works. Section 3 describes the basic ideas and design challenges. The proposed shoelace-based QoS routing protocol is presented in Sect. 4. To illustrate the performance of the proposed scheme, the simulation results are examined in Sect. 5. Finally, Sect. 6 concludes this paper.

2 Related Works

This paper focuses on developing a QoS routing protocol to support various network bandwidth. Recently, Lin and Liu [17] have proposed a QoS routing protocol that contains bandwidth calculation and slot reservation for multi-hop mobile networks. In MAC sub-layer, Lin et al. adopt the CDMA-over-TDMA channel model, such that CDMA is overlaid on top of the TDMA infrastructure; namely, multiple sessions can share the same TDMA slot via CDMA. Under such a model, the use of a time slot on a link only depends on the status of its one-hop neighboring links. Chen et al. [5] have extended this result to develop an on-demand, link-state, multi-path QoS routing protocol in a wireless mobile ad-hoc network. The protocol offers a bandwidth routing protocol for QoS support in a multi-hop mobile network. In addition, it calculates the end-to-end bandwidth and allocates bandwidth at the destination and collects link bandwidth information from the source to the destination so as to construct a network topology with the information of link bandwidth at the destination. In general, the bandwidth in the time-slotted network system is measured in terms of the amount of free slots. To satisfy a given bandwidth requirement, the bandwidth of the QoS route is calculated at the destination so as to accurately determine the uni-path or multi-path QoS route according to the bandwidth of the networks. The routing scheme offer a multi-path route if the bandwidth of the MANET is insufficient, and provide a uni-path route if the bandwidth of the MANET is sufficient. However, Chen et al.'s routing protocol is determined at the destination. It is similar to a centralized scheme. Liao et al. [15] propose an on-demand protocol for searching a multi-path QoS route from the source host to the destination host, where a multi-path is a network with a source and a sink satisfying the certain bandwidth requirement. The basic idea is to distribute a number of tickets from the source, which can be further partitioned into sub-tickets to search for a satisfactory multi-path. By using tickets to confine the number of route-searching packets, this protocol can avoid an unwise blind flooding. Since this protocol is based on an on-demand manner to search for a QoS route, no global link state information is needed to be collected in advance.

Furthermore, Chen and Ko [3] have proposed a lantern-tree-based QoS on-demand multicast protocol for MANETs, where the MAC sub-layer adopts the well-known CDMA-over-TDMA channel model. Under such a model, they identify a lantern-based tree in a MANET to provide an on-demand QoS multicast protocol to satisfy certain bandwidth requirements from a source to a group of destination nodes. The number of lanterns in a lantern-path depends on the status of the network bandwidth. In addition, the protocol also offers a simple reliable mechanism to guarantee reliable communications. However, these QoS multicast protocols typically assume the use of omni-directional antennas by all the nodes. With omni-directional transmission, the distribution of energy in all directional other than just the intended direction generates unnecessary interference to other nodes thereby considerably reduces network capacity.

Hamdaoui and Ramanathan [9] first present a link-bandwidth calculation algorithm that wireless nodes equipped with directional antennas can use to determine the available link bandwidth to any of their neighbors. They use the link-bandwidth calculation algorithm to propose an end-to-end flow QoS routing scheme for static wireless ad-hoc networks using directional antennas. Saha et al. [24] proposed a scheme for supporting priority-based QoS in mobile ad hoc networks by classifying the traffic flows in the network into different priority classes, and giving different treatment to the flow-rates which belong to different classes. This paper has adopted a control-theoretic approach to adaptively control the low-priority flows so as to maintain the high priority flow-rates at their desired level, and thus can guarantee QoS to high-priority flow. Their objective is to adaptively maximize low priority flows

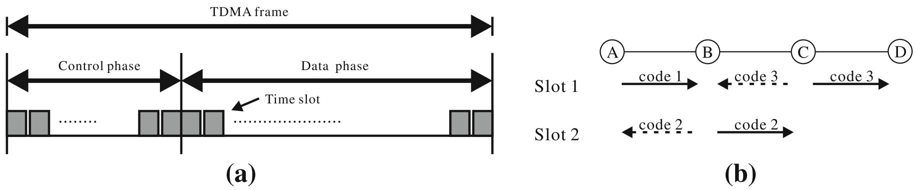

Fig. 1 **a** TDMA frame structure. **b** CDMA-over-TDMA

while maintaining high priority flows at a desired level so that full utilization of wireless medium can be achieved through adaptive rate control. The low priority flows, causing interference to high priority flow, detect and measure the high priority flow-rate at each node on their routes and consequently adjust their flow-rates using a feedback control mechanism to maintain the high priority flow at its desired level. They modified the scheme to show the overall improvement in throughput by using directional antennas. Ueda et al. [26] use the notion of zone-disjoint routes to avoid the contention between high and low priority routes by reserving the high priority communication zone. The primary objective is to devise a priority based routing scheme, which will protect the high priority flows from the contention caused by the low priority flows. Low priority flows will try to avoid this zone by selecting routes that is maximally zone-disjoint with respect to the high priority reserved zone and will consequently reduce the contention between high and low priority flows in that reserved zone. If a low priority flow has to go through high priority reserved zone causing interference then it will block itself temporarily to allow contention-free transmission of high priority flows and later may resume the blocked communication if possible. However, above-mentioned researches use uni-path scheme. If the network environment is strictly limited or some nodes move away, the QoS routing will fail. To guarantee high priority flows' QoS requirement, the low priority flows need to reduce or block its flow resulting in reducing the performance of all networks.

Using omni-directional antennas in MANET, two close nodes in different routing path interfere with each other and reduce the wireless medium utilization resulting in wasting the network capacity. When the QoS routing provides uni-path scheme, the routing fails easily once the network bandwidth is limited. Therefore, this paper proposes a shoelace-based routing protocol using directional antennas and adopts the structure of multi-path to achieve the QoS requirement. The scheme not only can adjust the path depending on the network bandwidth but also can decrease interference to other nodes.

3 System Model and Basic Idea

The MAC sub-layer in our model is implemented by using the CDMA-over-TDMA channel model [3,5,16,17]. Figure 1a displays that each frame is divided into a control phase and a data phase. Figure 1b shows that the CDMA is overlaid on top of the TDMA infrastructure. Multiple sessions can share a common TDMA time slot via CDMA, such that it can improve the performance of throughput. To overcome a hidden-terminal problem, an orthogonal code used by a host should differ from that used by any of its two-hop neighbors. A code assignment protocol should be supported. The bandwidth requirement is realized by reserving time slots on links. Under this channel model, the use of a time slot on a link only depends on the status of its one-hop neighboring links. This model may be emulated by WLAN cards

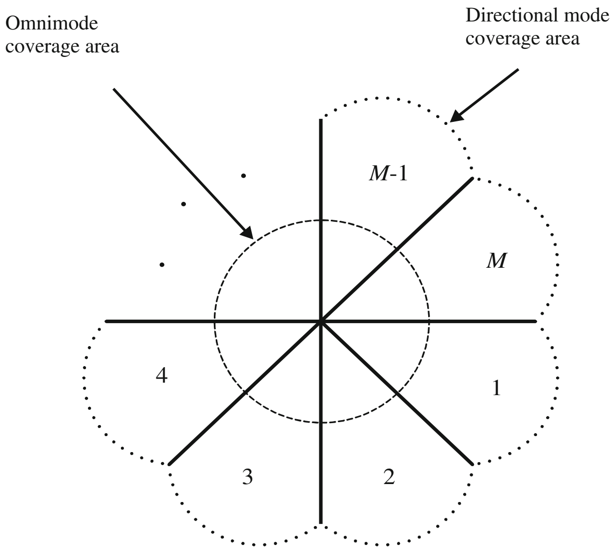

Fig. 2 A node with *M* sectors

which follow the IEEE 802.11 standard. Each data phase of a TDMA frame is assumed to be partitioned into several time slots.

All nodes in a region share a wireless channel and communicate on that shared channel. A directional antenna can transmit over a small angle (e.g. 45°), and several directional antennas may be used together to cover all directions. In this study, each node equips with directional antennas and has a unique node identifier. Figure 2 illustrates that an area around the node is covered by M sectors [12]. We assume that the sectors are not overlapping. We number the sectors from 1 to M starting from the sector that is located just right of the 3'o clock position. The node can transmit its signal to anyone of the M sectors and increase the coverage range of the transmission toward a specific direction. In the idle mode the node hears all the directions. In the reception of a signal, the node uses the selection diversity, which means that it uses the signal from the antenna that is receiving the maximum power of the desired signal. With this mechanism the receiver can extend the communication area, which means that the communication link can benefit more by sector-forming at both transmitter and receiver.

A QoS path is a path which satisfies a given bandwidth requirement from a source node to a destination node. This paper mainly introduces a special multi-path structure from a source to a destination which satisfies a given bandwidth requirement. Using the directional antenna has many benefits, for example, spatial reuse, enhancing transmission range, and saving power. This paper employs these benefits to achieve QoS routing. In Fig. 3a, consider a pair of two-hop neighbor nodes B and G; a QoS path is requested between nodes B to G which satisfies a bandwidth requirement B_r. Figure 3a shows that it only provides a uni-path routing, when the network bandwidth is sufficient. If the actual network bandwidth $B_{\overline{BG}}$ between nodes B and G is less than B_r ($B_{\overline{BG}} \leq B_r$), then give a pair of two-hop neighboring nodes B and G, one or more sub-paths exist between B and G, and the total bandwidth of one or more sub-paths is equal to B_r. The nature of multi-path is to increase the success rate of identifying a QoS route and providing a robust and reliable mechanism. The main concept of this paper is to use directional antennas to form a shoelace path and thus find out more paths to achieve QoS requirement. Figure 3b illustrates that these results are

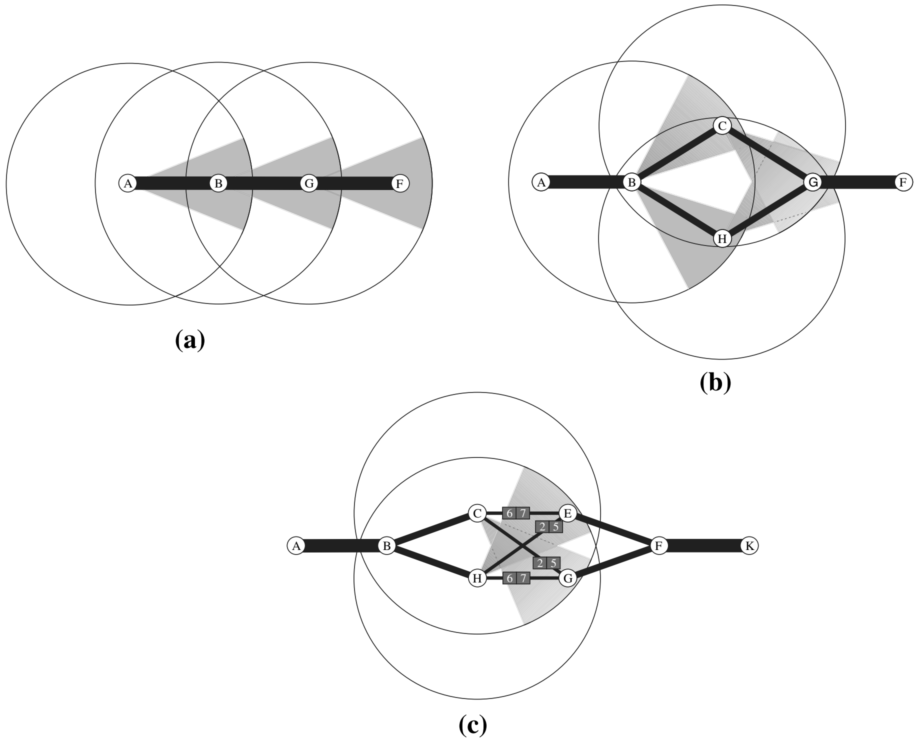

Fig. 3 Examples of different QoS routes with directional antennas. **a** Uni-path route. **b** Multi-path route. **c** Shoelace-path route

similar to Lantern [3]. However, in this paper, we use the directional antenna model to obtain more success rate of identifying a QoS route, because the directional antenna can enhance transmission range resulting in finding more nodes. The multi-path inherits the advantage of the robust and reliable mechanisms and a high success rate of searching for a QoS route.

Definition 1 *Shoelace*: Given a group of one-hop neighboring node, $\begin{bmatrix} h_1 & k_1 \\ h_2 & k_2 \\ \vdots & \vdots \\ h_m & k_n \end{bmatrix}$, node h_i connects with node k_j, where $m, n > 1$. By using the directional antenna, the link $\overline{h_i k_{j+1}}$ and $\overline{h_{i+1} k_j}$ form a cross link and can use the same time slot $\{t_1, t_2, \ldots, t_n\}$ to transmit data without interfering with each other, where $i = 1, \ldots, m$, $j = 1, \ldots, n$, and $n \geq 1$. The total bandwidth of all links between nodes h_i and k_j is equal to B_r. These cross links are denoted as a shoelace.

Figure 3c gives an example about the concept of the shoelace. Each sub-path is responsible for a sub-bandwidth requirement. The number of sub-paths is dependent on the network bandwidth. When the network bandwidth is strictly limited, it offers a shoelace-path routing as illustrated in Fig. 3c. The total actual bandwidth $B_{\overline{BC}}$ and $B_{\overline{BH}}$ is equal to the bandwidth B_r, but the bandwidth of next hop is insufficient. The scheme finds out other node E to make nodes C and H both connecting to node E. In the case, these links $\begin{bmatrix} C & E \\ H & G \end{bmatrix}$ appear to be

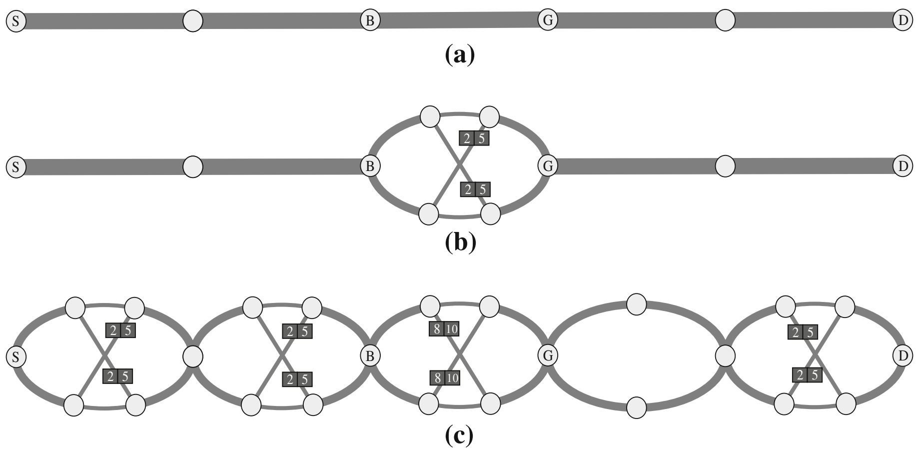

Fig. 4 Examples of (**a**) uni-path, (**b**) shoelace-path, (**c**) worst-case situation of a shoelace-path

crossed. Because this paper uses directional antennas, the cross paths do not interfere with each other and can transmit packet simultaneously, and thus reduces end-to-end delay. In addition, the proposed protocol employs fewer nodes and can find more paths to form a QoS route. This enables more other nodes to be used by other QoS routes and thus enhancing the utilization of wireless medium and saving power by keeping more other nodes idle.

Continuing, consider a QoS route requested from the node S to the node D which satisfies the bandwidth requirement B_r as given in Fig. 4a.

Definition 2 *Shoelace-path*: Give a path from a source to a destination, if one or more shoelaces exist in the path, the path is denoted as a shoelace-path.

Figure 4b displays that only one shoelace-path exists in the path, and there are four shoelace-paths and a multi-path in the path as shown in Fig. 4c. If we cannot find a uni-path from S to D, a QoS route with shoelace-paths (or multi-paths) is identified. A QoS route with a fewer number of shoelace-paths (or multi-paths) will be recognized if the network bandwidth is sufficient. If the network bandwidth is strictly limited, a QoS routes with a greater number of shoelace-paths will be constructed.

The solve the problem of out-of-order delivery. Each time when the packet is splitted to the shoelace path or multi-path, an extra sequence number is added to each sub-packet. The length of the extra-sequence number is set according to the number splitted sub-packets. When these sub-packets are received by the convergent node, it can reassemble these sub-packets according to the extra sequence numbers.

4 Shoelace-based QoS Routing Protocol

The proposed routing protocol mainly constructs the shoelace-path from source to destination. The shoelace-based protocol is achieved by the following three phases: namely the shoelace identification, shoelace-path discovery and shoelace-path maintenance. The shoelace identification phase contains shoelace identification and time slot reservation for mobile ad hoc networks. The shoelace-path discovery phase constructs the shoelace-path from the source to the destination. The shoelace-path maintenance phase maintains the shoelace-path structure for the sake of enhancing the robustness and keeping a stable QoS route.

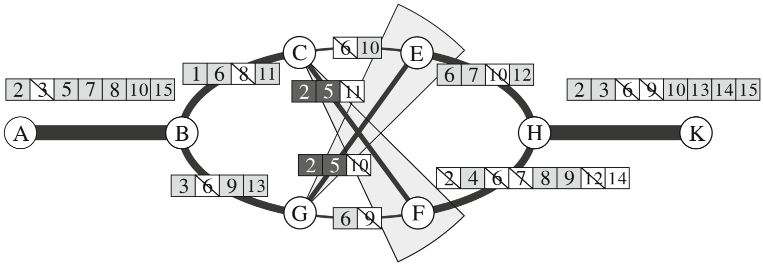

Fig. 5 Identifying of shoelace and link reserved time slot

4.1 Phase I: Shoelace Identification

The shoelace-based QoS route is constructed after collecting the link-state information for all nodes in the MANET. $[n_1, n_2, n_3, \ldots, n_k]$ denotes a path from node n_1 to node n_k. In Fig. 5, there are four sub-paths $[B, C, E, H]$, $[B, C, F, H]$, $[B, G, E, H]$, and $[B, G, F, H]$ exist between node B and node H, and a shoelace occurs. Let $\begin{bmatrix} & h_1 & k_1 & \\ & h_2 & k_2 & \\ \alpha & \vdots & \vdots & \beta \\ & h_m & k_n & \end{bmatrix}$ denote a shoelace-based sub-path between α and β, where $[\alpha, h_1, k_1, \beta]$, $[\alpha, h_1, k_2, \beta]$, $\ldots$, $[\alpha, h_m, k_{n-1}, \beta]$, …, and $[\alpha, h_m, k_n, \beta]$ are sub-paths between α and β. For example as shows in Fig. 5, $\begin{bmatrix} B & \begin{matrix} C & E \\ G & F \end{matrix} & H \end{bmatrix}$ denote a shoelace-based sub-path between B and H. Further, each node decides the reserved time slots with its neighbors.

Each node periodically maintains the hello message to construct shoelaces and collect local link-state information for each node in the MANET, where the lifetime of hello message is two-hop. With the hello messages, each node can collect all local link-state information from all two-hop neighboring nodes. Since the MAC layer adopts the CDMA-over-TDMA channel model, the time slots reservation of $\begin{bmatrix} & h_1 & k_1 & \\ & h_2 & k_2 & \\ \alpha & \vdots & \vdots & \beta \\ & h_m & k_n & \end{bmatrix}$ has the following rules:

R1: Time slots reserved on all links $\overline{\alpha h_i}$ must be different, where $1 < i < m$.
R2: Time slots reserved on all links $\overline{k_j \beta}$ must be different, where $1 < j < n$.
R3: Time slots reserved on link $\overline{\alpha h_i}$ and $\overline{h_i k_j}$ must be different, where $1 < i < m$, $1 < j < n$.
R4: Time slots reserved on link $\overline{h_i k_j}$ and $\overline{k_j \beta}$ must be different, where $1 < i < m$, $1 < j < n$.
R5: Time slots reserved on link $\overline{h_i k_j}$ and $\overline{h_{i'} k_{j'}}$ must be different, where $i = i'$ or $j \neq j'$.

Figure 5 illustrates an example for these rules. Based on R1, the reserved time slots on link $\overline{BC} = \{1, 6, 11\}$ and on link $\overline{BG} = 3, 9, 13\}$ must be different; based on R2, the reserved time slots on link $\overline{EH} = \{6, 7, 12\}$ and on link $\overline{FH} = \{4, 8, 9\}$ must be different; based on R3, the reserved time slots on link $\overline{BC} = \{1, 6, 11\}$ and on link $\overline{CF} = \{2, 5\}$ must be different; based on R4, the reserved time slots on link $\overline{GE} = \{2, 5\}$ and on link $\overline{EH} = \{6, 7, 12\}$ must be different; based on R5, the reserved time slots on link $\overline{CE} = \{10\}$ and on link $\overline{CF} = \{2, 5\}$ must be different. Although links $\overline{CF}$ and $\overline{GE}$ are cross links, they can still transmit data in the same time slots, $\{2, 5\}$, without interfering each other.

To calculate the reserved time slots between two nodes, some symbol is defined as follows.

- $F[i]$: a set of free time slots of node i. $F[i] = t_1, t_2, t_3, \ldots, t_k$, where t_k is a time slot.
- $SF[i, j]$: a set of share free time slots of nodes i and j. $SF[i, j] = F[i] \cap F[j]$.
- $RSF[i, j]$: a set of reserved share free time slots of nodes i and j. RSF is a subset of ASF. $RSF[i, j] = \{t_k, t_k \in ASF[i, j]\}$.
- $ASF[i, j]$: a set of available share free time slots of nodes i and j.
- $ASF[i, j] = SF[i, j] - RSF[x, i] - RSF[y, j]$ where x belongs to node i's neighbors (except node j) and y belongs to node j's neighbors (except node i).

Figure 5 illustrates the calculating result. $SF\ [F, H] = \{2, 4, 6, 7, 8, 9, 12, 14\}$, $ASF\ [F, H] = SF[F, H] - RSF[C, F] - RSF[G, F] - RSF[E, H] - RSF[H, K] = \{2, 4, 6, 7, 8, 9, 12, 14\} - \{2, 5\} - \{6\} - \{6, 7, 12\} - \{2, 3, 10, 13, 14, 15\} = \{4, 8, 9\}$. RSF is a subset of ASF. $RSF[F, H]$ could be $\{4\}$, $\{8\}$, $\{9\}$, $\{4,8\}$, $\{4,9\}$, $\{8,9\}$, or $\{4, 8, 9\}$. After calculating, the cross links $\overline{CF}$ and $\overline{GE}$ can transmit data using the same time slots $\{2, 5\}$ without interfering each other. In this paper, the bandwidth in the time slotted network is represented by the amount of free time slots. Therefore the actual available bandwidth is $|ASF|$. Afterward, this paper uses $|RSF|$ to denote the reserved bandwidth.

4.2 Phase II: Shoelace-Path Discovery

Each node employs the hello message to find neighbors' locations and neighbors' free time slots by using directional antennas and calculates the reserved time slots of its links. Each node maintains two-hop neighbors' information by exchanging the hello message. The source node initiates a bandwidth requirement packet SL_REQ and broadcasts this packet to its neighbors. Each packet record the bandwidth requirement B_r and link-state information. For each bandwidth request, the source node may set a number of SL_REQ. The SL_REQ packet's format is denoted as SL_REQ (S, D, NH, TH_NEI, NL, RSF , B_r, B), where each field of the packet is defined as follows:

- S: the source node's address.
- D: the destination node's address.
- NH: the node which is the neighbor of the current sender and has received a SL_REQ packet.
- TH_NEI: common neighbors of the current sender's next hop nodes. For example in Fig. 5, the common neighbors of node B's next hop nodes (e.g. nodes C and G) are nodes E and F.
- NL: a list of nodes, which denotes the visited nodes from the source to the current traversed node;
- RSF: a list of reserved time slots. This field records the reserved time slots between the current node and the next hop node.
- B_r: the bandwidth requirement from the source to the destination.
- B: the total bandwidth from the current node to its neighbors.

Based on the network environment, there are three cases in this paper.

Case I: when the network bandwidth is sufficient, each node detects that the bandwidth between itself and its neighbors is satisfactory. The uni-path is used as the routing path.

Case II: when the network bandwidth is insufficient and the uni-path is unsuitable. The node finds more sub-paths such that the total bandwidth are equal to B_r. The multi-path result is used. Give a path [$n1$ $n2$ $n3$ $n4$], $B_{\overline{n_1 n_2}}$ is equal to B_r and $B_{\overline{n_2 n_3}}$ is less then B_r. The procedure is described as follows:

Procedure I:

Step 1: if $B_{\overline{n_2 n_3}}$ is less than B_r, then node n_2 finds out other nodes n'_i, where $i = 1, 2, \ldots,$ m, such that the total bandwidth on $\begin{bmatrix} & n'_1 \\ n_2 & \vdots \\ & n'_m \end{bmatrix}$ is equal to B_r and calculates the *RSF* $[n_2, n_3]$, $RSF[n_2, n'_1]$, $RSF[n_2, n'_2]$,..., and $RSF[n_2, n'_m]$. Node n_2 then records the sector ID which n_2 uses to connect with nodes n'_i and n_3, updates the SL_REQ (S, D, $n'_i(n_3)$, n_4, $\{[n_1\ n_2]\}$, $RSF[n_2, n'_i]$, B_r, B) and sends routing packet to notify nodes n_3 and n'_i the reserved share free time slots and two hop neighbor n_4's information.

Step 2: when node n_3 and n'_i received the routing packet from node n_2, they respectively calculate $RSF = \{t_1, t_2, \ldots, t_k\}$, where $k \geq 1$, with their common neighbor n_4 which has been notified by node n_2. Node n_3 and n'_i then update the SL_REQ (S, D, n_4, *TH_NEI* $=$ {two hop neighbors of node $n'_i(n_3)$, $\{[n_1\ n_2\ \ n'_i(n_3)]\}$, $RSF[n'_i, n_4]$, B_r, $B = |RSF[n'_i, n_4]|$) and forward the routing packet to next hop. Nodes n_3 and n'_i record the sector ID which they use to connect to next hop and receive from preceding hop.

Step 3: node n_4 received routing packet from n_3 and n'_i and the bandwidth on $\begin{bmatrix} n_3 & \\ n'_1 & \\ \vdots & n4 \\ n'_m & \end{bmatrix}$ is equal to B_r. Now the multi-path $\begin{bmatrix} & n_3 & \\ & n'_1 & \\ n_2 & \vdots & n_4 \\ & n'_m & \end{bmatrix}$ is constructed, where $m \geq 1$.

Figure 6 illustrates this situation. In Fig. 6a, the bandwidth requirement B_r is set to six, and the uni-path [A , B, C, F] does not satisfy the QoS requirement in link $B_{\overline{BC}}$. To satisfy the bandwidth requirement, the improved method is started. First, node B finds other node G such that the total bandwidth on $\begin{bmatrix} B & C \\ & G \end{bmatrix}$ is equal to B_r and calculates $RSF[B, C] = \{3, 4, 6, 11\}$ and $RSF[B, G] = \{1, 13\}$. Node B sends routing packet to notify nodes C and G

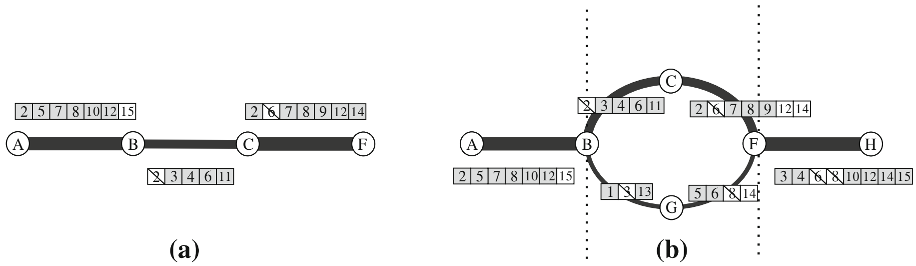

Fig. 6 Example of that uni-path is unsuitable. **a** A uni-path that cannot satisfies the bandwidth requirement. **b** A multi-path that can satisfies the bandwidth requirement

the reserved share free time slots and node F's information. Second, when nodes C and G received the routing packet from node B, node C calculates $RSF[C, F] = \{2, 7, 8, 9\}$ and node G calculates $RSF[G, F] = \{5, 6\}$. Nodes C and G forward routing packet to node F. Final, node F received the routing packet from nodes C and G and the bandwidth on $[C\ F]$ is equal to B_r. Now the multi-path $\left[B \begin{smallmatrix} C \\ G \end{smallmatrix} F\right]$ is constructed as shown in Fig. 6b.

Case III: based on the preceding multi-path network topology, some parts of the bandwidth are insufficient due to the network bandwidth is strictly insufficient. The shoelace-path is used. Two procedures are designed according to the insufficient parts of the bandwidth.

Procedure II-A: Let $\left[\begin{matrix} & h_1 & \\ n_1 n_2 & \vdots & n_5 n_6 \\ & h_p & \end{matrix}\right]$ denotes the multi-path, where $p \geq 2$. The rear of the multi-path's bandwidth does not satisfy the bandwidth requirement. Now the total bandwidth on $\left[\begin{matrix} h_1 & \\ \vdots & n_5 \\ h_p & \end{matrix}\right]$ is less than B_r. $B_{\overline{n_2 h_i}} = |RSF[n_2\ h_i]| < B_r$, $B_{\overline{h_i n_5}} = |RSF[\ h_i\ n_5]| < B_{\overline{n_2 h_i}}$. The operations are described as follows:

Step 1: node h_i finds out other node k_j, which has been notified by node n_2, where $i = 1, 2, \ldots, p$, and $j = 1, 2, \ldots, m$, such that the bandwidth on $[h_i k_j]$ is equal to that on $[n_2 h_i]$ and calculates $RSF[h_i, k_1]$, $RSF[h_i, k_2], \ldots$, and $RSF[h_i, k_m]$, respectively. Then node h_i updates the SL_REQ (S, D, $k_j(n_5)$, n_6, $\{[\ n_1\ n_2\ h_i]\}$, $RSF[h_i\ k_j]$, B_r, $B = |RSF[h_i\ k_j]|$) and sends routing packet to notify nodes k_j the reserved share free time slots and two hop neighbor n_6's information and records the sector ID which node h_i uses to connect with node k_j.

Step 2: when node k_j received the routing packet from node h_i, k_j calculates $RSF[k_j, n_6] = \{\ t_1, t_2, \ldots, t_m\}$, where $m \geq 1$. The node n_5 calculates $RSF[\ n_5, n_6] = \{t_1, t_2, \ldots, t_m\}$, where $m \geq 1$, again due to the change of the traffic from node h_i. Nodes n_5 and k_j update the SL_REQ (S, D , n_6, $TH\_NEI =$ {two hop neighbors of node $k_j(n_5)$}, $\{[n_1\ \ n_2\ h_i\ k_j(n_5)]\}$, $RSF[k_j(\ n_5), n_6]$, B_r, $B = |RSF[k_j, n_6]|$) and forward the routing packet to next hop and record the sector ID which node n_5 and k_j use to connect with next hop and receive from preceding hop.

Step 3: node n_6 received the routing packets from node n_5 and nodes k_j and the total bandwidth on $\left[\begin{matrix} n_5 & \\ k_1 & \\ \vdots & n_6 \\ k_m & \end{matrix}\right]$ is equal to B_r. The shoelace $\left[\begin{matrix} & h_1 & n_5 & \\ & & k_1 & \\ n_2 & \vdots & \vdots & n_6 \\ & h_q & k_m & \end{matrix}\right]$, where $q \geq 2$, $m \geq 1$ is constructed.

Figure 7 illustrates this case. The rear part of the total bandwidth on the multi-path $\left[AB \begin{smallmatrix} C \\ G \end{smallmatrix} FH\right]$ does not satisfy the bandwidth requirement. Figure 7a shows a situation in this case, $B_{\overline{GF}}$ is insufficient resulting in the total bandwidth on $\left[\begin{smallmatrix} C \\ G \end{smallmatrix} F\right]$ is less then B_r. To satisfy the bandwidth requirement, the improved method is started. First, node G finds out

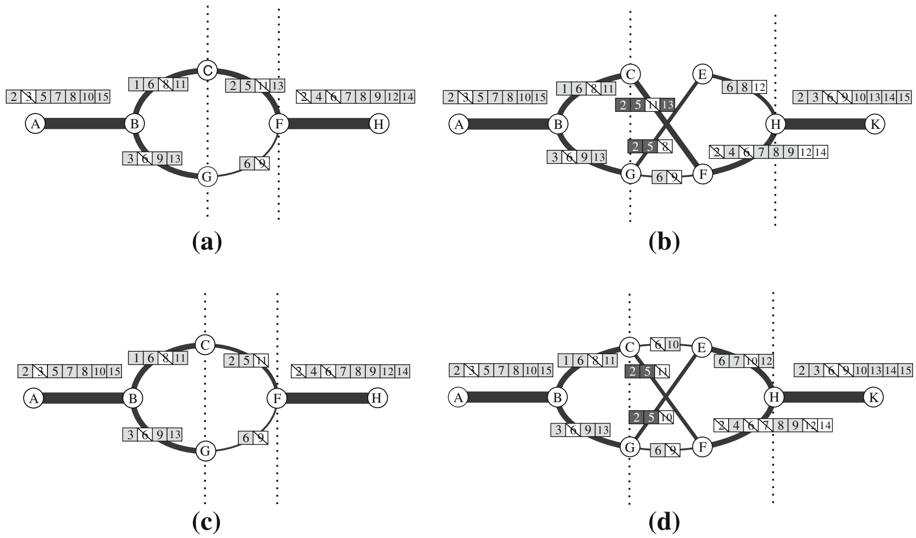

Fig. 7 Example of shoelace-path with insufficient rear-bandwidth. **a**, **c** The multi-path does not satisfy the bandwidth requirement. **b**, **d** The shoelace-path can exploit more bandwidth to satisfy the bandwidth requirement

other node E and calculates $RSF[G, E] = \{2, 5\}$. Node G then sends routing packet to notify node E the reserved share free time slot and node H's information. Second, node E received the routing packet from node G, and then node E calculates the $RSF[E, H] = \{6, 8\}$. Node F calculates $RSF[F, H] = \{4, 7, 8, 9\}$ again. Nodes E and F forward the routing packet to node H. Finally, node H reserved the routing bandwidth between nodes E and F and the total bandwidth on $\begin{bmatrix} E \\ F \end{bmatrix} H$ is equal to B_r. The shoelace $\begin{bmatrix} B \begin{smallmatrix} C & E \\ G & F \end{smallmatrix} H \end{bmatrix}$ is constructed as shown in Fig. 7b. Figure 7c shows another situation in this case, $B_{\overline{CF}}$ and $B_{\overline{GF}}$ are insufficient resulting in the total bandwidth on $\begin{bmatrix} \begin{smallmatrix} C \\ G \end{smallmatrix} F \end{bmatrix}$ is less then B_r. First, the nodes C and G find out node E and calculate $RSF\ [C, E] = \{10\}$ and $RSF[G, E] = \{2, 5\}$, respectively. Nodes C and G forward the routing packet to notify node E the reserved share free time slots and node H's information. Second, node E calculates $RSF[\ E, H] = \{6, 7, 12\}$ and node F calculates RSF $[F, H] = \{4, 8, 9\}$ again. Then nodes E and F forward the routing packet to node H. Final, node H reserved the routing bandwidth between nodes E and F and the total bandwidth on $\begin{bmatrix} \begin{smallmatrix} E \\ F \end{smallmatrix} H \end{bmatrix}$ is equal to B_r. The shoelace $\begin{bmatrix} B \begin{smallmatrix} C & E \\ G & F \end{smallmatrix} H \end{bmatrix}$ is constructed as show in Fig. 7d.

Procedure II-B: The total bandwidth on $\begin{bmatrix} & h_1 & \\ n_2 & \vdots & n_5 \\ & h_p & \end{bmatrix}$ is less than B_r. The front and rear of the multi-path's bandwidth doe not satisfy the bandwidth requirement. But there are extra bandwidth on one or more links. Now let there be extra bandwidth on link $\overline{n_2 h_1}$. The operation is described as follows.

Step 1: node n_2 finds out other node h'_i, where $i = 1, 2, \ldots, x$, $x \geq 1$, such that the total bandwidth on $\begin{bmatrix} & h'_1 \\ & \vdots \\ n_2 & h'_x \\ & h_1 \\ & \vdots \\ & h_p \end{bmatrix}$ is equal to B_r and calculates $RSF[n_2, h'_1]$, $RSF[n_2, h'_2], \ldots$, $RSF[n_2, h'_x]$. Afterward, node n_2 updates SL_REQ (S, D, h_i, $TH_NEI = \{$two hop neighbors of node $n_2\}$, $\{[n_1\ n_2]\}$, $RSF[n_2, h'_i]$, B_r, $B = \{|RSF[n_2, h'_i]|\}$) and sends routing packet to notify h'_i the reserved share free time slots and two hop neighbor's information and records the sector ID which node n_2 uses to connect with node h'_i.

Step 2: when node h'_i received the packet from node n_2, node h'_i calculates the $RSF[h'_i, n_5] = \{t_1, t_2, \ldots, t_m\}$, where $m \geq 1$. Node h_1 finds out other node k_i, where $i = 1, 2, \ldots, m$, $m \geq 1$, such that the bandwidth on $\begin{bmatrix} & k_1 \\ h_1 & \vdots \\ & k_m \end{bmatrix}$ is equal to on $[n_2\ h_1]$ and calculates $RSF[h_1, k_i] = \{t_1, t_2, \ldots, t_m\}$, where $m \geq 1$. Nodes h_1 and h'_i update the SL_REQ (S, D, k_j, $TH_NEI = \{$two neighbors of node $h'_i(h_1)\}$, $RSF[h'_i(h_1), k_j]$, B_r, $B = |RSF[h'_i(h_1)]|$) and forward the routing packet to next hop and record the sector ID which nodes h_1 and h'_i use to connect with next hop and receive from preceding hop.

Step 3: when nodes n_5 and k_i received the routing packet from nodes h'_i and h_1, nodes n_5 and k_i calculate $RSF[n_5, n_6]$ and $RSF[k_i, n_6]$, respectively. Nodes n_5 and k_i update the SL_REQ (S, D, n_6, $TH_NEI = \{$two neighbors of node $k_j(n_5)\}$, $RSF[k_j(n_5), n_6]$, B_r, $B = |RSF[k_j(n_5), n_6]|$) and forward the routing packet to next hop and record the sector ID which nodes n_5 and k_i use to connect with next hop and receive from preceding hop.

Step 4: node n_6 received the routing packet form nodes n_5 and k_i and the total bandwidth on $\begin{bmatrix} k_1 & \\ \vdots & n_6 \\ k_m & \\ n_5 & \end{bmatrix}$ is equal to B_r. The shoelace $\begin{bmatrix} & h'_1 & & \\ & \vdots & k_1 & \\ n_2 & h'_x & \vdots & n_6 \\ & h_1 & k_m & \\ & \vdots & n_5 & \\ & h_p & & \end{bmatrix}$ is constructed.

Figure 8 illustrates this case. The front and rear part of the total bandwidth on the multi-path does not satisfy the bandwidth requirement. In Fig. 8a, the total bandwidth on $\begin{bmatrix} B & C & F \\ & G & \end{bmatrix}$ is less than B_r and there are extra bandwidth on link $\overline{BG}$. To satisfy the bandwidth requirement, the improved method is started. First, node B finds out other node E and calculates the $RSF[B, E] = \{4, 12\}$. Node B sends the routing packet to notify node E the received share free time slots and node F's information. Second, when node E received the routing packet from node B, node E calculates the $RSF[E, F] = \{8, 10\}$. Node G finds out other node K and calculates the $RSF[G, K] = \{8, 10\}$. Nodes E and G forward the routing packet to nodes F and K, respectively. Third, nodes K and F received the routing packet from nodes G and E

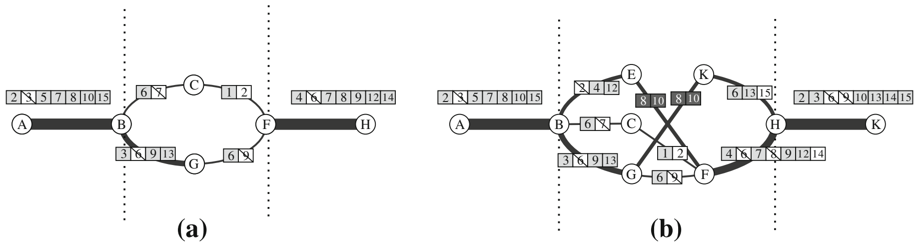

Fig. 8 Example of shoelace-path with insufficient total bandwidth. **a** The multi-path does not satisfy the bandwidth requirement. **b** The shoelace-path can exploit more bandwidth to satisfy the bandwidth requirement

and calculate $RSF[K, H] = \{6, 13\}$ and $RSF[F, H] = \{4, 7, 9, 12\}$, respectively. Then nodes K and F send routing packet to node H. Final, node H received the routing packet from nodes K and F and the total bandwidth on $\begin{bmatrix} \begin{matrix} K \\ F \end{matrix} & H \end{bmatrix}$ is equal to B_r. The shoelace $\begin{bmatrix} B & \begin{matrix} E \\ C \\ G \end{matrix} & \begin{matrix} K \\ F \end{matrix} & H \end{bmatrix}$ is constructed as show in Fig. 8b.

Observing preceding various cases, we propose a formal procedure for various cases. The detail of shoelace-based protocol is given as follow:

Step 1: the source node S calculates $RSF[S, j]$, where j is its neighbor ID, then node S chooses one or more nodes such that the total bandwidth of the links between node S and its neighbors is equal to B_r. The source node initiates and transmits a SL_REQ (S, D, NH, TH_NEI, $NL = \{[S]\}$, RSF, B_r, B) packet to next hop node toward the destination node D if the bandwidth requirement is B_r. The source node records the sector ID which it uses to connect with node j.

Step 2: if node e receives a number of SL_REQ packet from node n_i, $i = 1, \ldots, n$, node e adds its ID into the NL, and four cases are considered. (1) if $\sum B = B_r$ and $B_{\overline{ek}}$ is less than B_r, where k is next hop of e, then run procedure I; (2) if $B < B_r$ and the bandwidth on $\overline{ek}$ is less than B, where k is next hop of e, then run procedure II-A; (3) if $\sum B = B_r$ and $B_{\overline{ek_i}}$ is less then B_r, where k_i is next hop of e, and one link $\overline{ek_j}$ has more bandwidth, then run procedure II-B; (4) if node e is the destination node, then go to step 3.

Step 3: the destination node D waits for a period of time to receive one or more SL_REQ. After a period of time, node D responds to the source node and the QoS routing path is constructed.

When the destination receives one or many different SL_REQ packets from the source, the QoS route is constructed. Then the data are transmitted in the reserved time slots. The shoelace-path search operation is executed based on the formal algorithm.

Let $\left[\begin{bmatrix} & h_1 & k_1 & \\ & h_2 & k_2 & \\ \alpha_1 & \vdots & \vdots & \beta_2 \\ & h_m & k_n & \end{bmatrix}, \ldots, \begin{bmatrix} & h_1 & k_1 & \\ & h_2 & k_2 & \\ \alpha_x & \vdots & \vdots & \beta_y \\ & h_m & k_n & \end{bmatrix} \right]$ denote a shoelace-path, where $\begin{bmatrix} & h_1 & k_1 & \\ & h_2 & k_2 & \\ \alpha_i & \vdots & \vdots & \beta_i \\ & h_m & k_n & \end{bmatrix}$ is the ith shoelace of the shoelace-path. Observe that $m, n \geq 1$ and the ith shoelace can be a uni-path or a Lantern [3]. The source node in the MANET executes the shoelace protocol and calculates the reserved time slot to check if a shoelace exists. If a shoelace exists, a

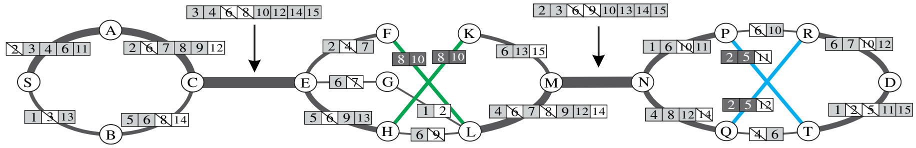

Fig. 9 Construction of a shoelace-path

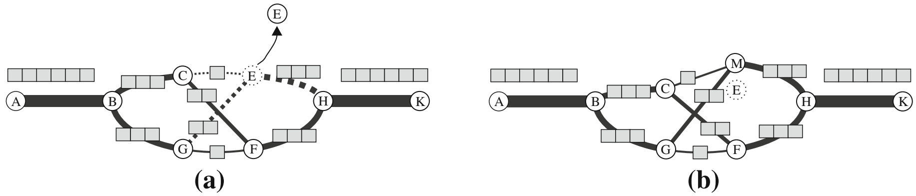

Fig. 10 Case of shoelace-path recovery. **a** Node E has moved away. **b** Node M has been found to replace node E

shoelace-path with one shoelace $\left[\alpha_i \begin{matrix} h_1 & k_1 \\ h_2 & k_2 \\ \vdots & \vdots \\ h_m & k_n \end{matrix} \beta_i\right]$ is constructed. Figure 9 gives an instance. The source node S detects that $B_{\overline{SB}}$ and $B_{\overline{SA}}$ is less than B_r. Then node S executes Procedure I. The multi-path $\left[S \begin{matrix} A \\ B \end{matrix} C\right]$ is constructed. Afterward, when node E detects that $\sum B = B_r$ and $B_{\overline{EH}}$, $B_{\overline{EG}}$, and $B_{\overline{EF}}$ are less than B_r and link $\overline{EH}$ has extra bandwidth, node E executes Procedure II-B. The shoelace $\left[E \begin{matrix} F \\ G \\ H \end{matrix} \begin{matrix} K \\ L \end{matrix} M\right]$ is constructed. When $B_{\overline{PR}} < B_{\overline{NP}}$, $B_{\overline{QR}} < B_{\overline{NQ}}$ and the total bandwidth $B_{\overline{PR}}$ and $B_{\overline{QR}}$ are less than B_r, node N executes Procedure II-A. The shoelace $\left[N \begin{matrix} P & R \\ Q & T \end{matrix} D\right]$ is constructed. Final, node D responds to the source node and the QoS shoelace-path $\left[S \begin{matrix} A \\ B \end{matrix} C\ E \begin{matrix} F \\ G \\ H \end{matrix} \begin{matrix} K \\ L \end{matrix} M\ N \begin{matrix} P & R \\ Q & T \end{matrix} D\right]$ is constructed.

4.3 Phase III: Shoelace-Path Maintenance

Since each node can move randomly, which leads the network topology to be dynamic. The maintenance procedure is used to maintain the bandwidth requirement. If the shoelace-path fails due to the total bandwidth is less than B_r, then the preceding hop nodes of the failed or moving node try to search other node to replace the failed or moving node. Figure 10 shows an example. Figure 10a shows that node E moves and link $\overline{CE}$, $\overline{GE}$, and $\overline{EH}$ are broken. The total bandwidth in $\left[B \begin{matrix} C \\ G \end{matrix} F\, H\right]$ is less than B_r. Then nodes C and G try to search other node M and set up link $\overline{CM}$, $\overline{GM}$, and $\overline{MH}$ such that the total bandwidth in $\left[B \begin{matrix} C & M \\ G & F \end{matrix} H\right]$ is equal to B_r as shown in Fig. 10b. When the QoS requirement can not be satisfied even using the maintenance operation due to the changes of the network topology, the protocol should restart the shoelace-path discovery procedure.

5 Performance Evaluation

This paper presents a shoelace-based QoS routing protocol for mobile ad hoc network. In this section, we evaluate the performance of our shoelace-based QoS routing protocol, Saha et al.'s priority-based flow-rate QoS control routing protocol [24], and Ueda et al.'s priority-based QoS routing protocol [26] with zone reservation and adaptive call blocking. All of these protocols have implemented a complete directional antenna module in NCTUns 3.0 simulator and emulator [19]. The moving speed of each host is from 0 to 50 km/h. The number of time slots in data phase of a frame is assumed to be 16 slots. The transmission range of 4, 6, 8, and 12 beam antenna is assumed to be 60, 70, 80, and 100 m, respectively. The bandwidth requirements are 1 to 8 time slots. The average usable network bandwidth is 6.25 to 50%. The data transmission rate is set as 2 Mb/s.

Afterward, this paper uses *Mo*, *Br*, *Bn*, and *Se* to denote the mobility, bandwidth requirement, average usable network bandwidth, and number of sector, respectively. The simulation is run in a 1000×1000 m^2 area with 50 mobile hosts. The source and destination are randomly selected. Once the QoS request is successful, a time slot is reserved for all the subsequent packets. The reservation is released when either the data transmission process is finished or the link is broken. A packet is dropped if the packet residing in a node exceeds the maximal queuing delay time which is set to four frame lengths (328 ms). The performance metrics are shown as follows:

- *Success rate*: the number of successful QoS routes divided by the total number of QoS requests from the source to the destination.
- *Throughput*: the number of received data packets for all the destination hosts divided by the total number of data packets sent from the source hosts.
- *Wireless medium utilization*: the number of received data packets for all the destination hosts divided by the simulation area.
- *Average latency*: the average source to destination delay encountered by each data packet.
- *Control overhead*: the total number of control packets.

It is worth mentioning that an efficient QoS routing protocol achieves with a higher success rate, higher throughput, and lower average latency. In the following subsections, we illustrate our simulation results of success rate, throughput, wireless medium utilization, average latency, and control overhead from various perspectives.

5.1 Success Rate

The simulation results of the zone-disjoint (Ueda), flow-control (Saha), and shoelace-based protocols are shown in Fig. 11 to reflect the performance of success rate. Figure 11a shows the performance of success rate vs. bandwidth requirement, where $1 \leq Br \leq 8$ time slots, with *Mo* fixed at 30 km/h, *Bn* fixed at 25%, and *Se* fixed at 8. The curves of all the protocols are close to each other when the bandwidth requirement is 1 time slots. When the bandwidth requirement is increased, the shoelace-based protocol is obvious better than the others. This is because the shoelace-based protocol can find other sub-path such that the total bandwidth on the sub-path is equal to the bandwidth requirement. Figure 11b shows the performance of success rate vs. average usable network bandwidth, where $6.25 \leq Bn \leq 50$ percentage,

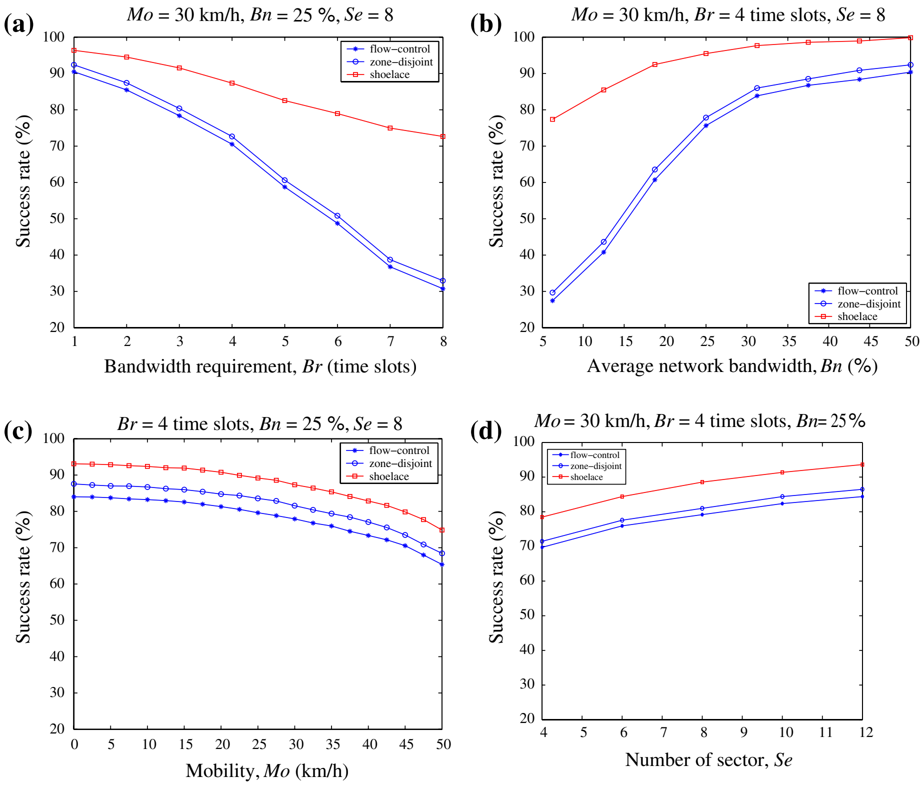

Fig. 11 Performance of (**a**) success rate vs. bandwidth requirement, (**b**) success rate vs. average usable network bandwidth, (**c**) success rate vs. mobility, (**d**) success rate vs. number of sectors

with *Mo* fixed at 30 km/h, *Br* fixed at 4 time slots, and *Se* fixed at 8. When the average usable network bandwidth is 6.25%, meaning the bandwidth is strictly insufficient, the shoelace scheme outperforms the others. This is because the shoelace scheme constructs the multi-path such that the total bandwidth on all sub-paths is equal to the bandwidth requirement. However, the zone-disjoint scheme and the flow-control scheme adapt uni-path. It is hard to discover a QoS route if only using uni-path, especially if the average network bandwidth is insufficient. Figure 11c shows the performance of success rate vs. mobility, where $0 \leq Mo \leq 50$ km/h, with *Br* fixed at 4 time slots, *Bn* fixed at 25%, and *Se* fixed at 8. All protocols have low success rate at higher mobility. A higher success rate indicates that a better scheme was achieved. From that point, the shoelace scheme is better than the others. Figure 11d shows the performance of success rate vs. number of sector, where $4 \leq Se \leq 12$, with *Mo* fixed at 30 km/h, *Br* fixed at 4 time slots, and *Bn* fixed at 25%. When the number of sector is increasing, the success rate is also increasing. This is because the greater number of sectors has farther transmission range and finds more suitable nodes to construct QoS routing path.

5.2 Throughput

Figure 12 illustrates the performance of throughput. The throughput is obtained by calculating the average of all the estimated throughput. Figure 12a shows the performance of

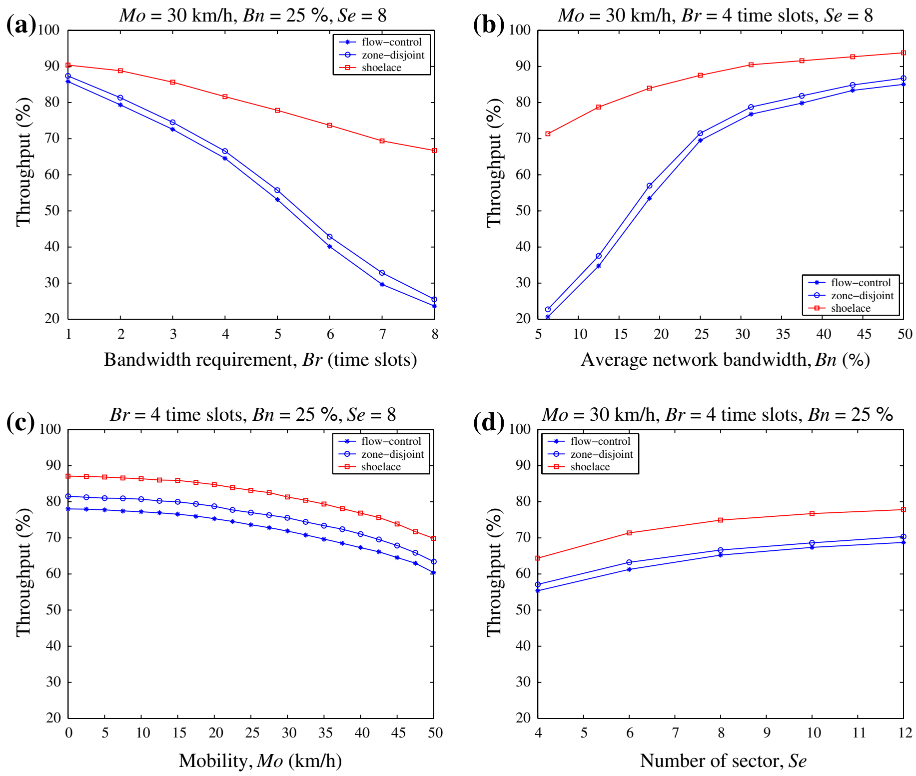

Fig. 12 Performance of (**a**) throughput vs. bandwidth requirement, (**b**) throughput vs. average usable network bandwidth, (**c**) throughput vs. mobility, (**d**) throughput vs. number of sector

throughput vs. bandwidth requirement, where $1 \leq Br \leq 8$ time slots, with *Mo* fixed at 30 km/h, *Bn* fixed at 25%, and *Se* fixed at 8. When the bandwidth requirement is increased, the shoelace-based protocol is obvious better than the others. This is because the higher bandwidth requirements easily lead to low priority flows and thus reduce their flow rate and block the flow in both flow-control scheme and zone-disjoint scheme, respectively. However, the bandwidth requirement is shared among multi-path in the shoelace scheme. Figure 12b shows the performance of throughput vs. average usable network bandwidth, where $6.25 \leq Bn \leq 50$ percentage, with *Mo* fixed at 30 km/h, *Br* fixed at 4 time slots, and *Se* fixed at 8. When the average network usable bandwidth is low, the shoelace scheme outperform the others. Figure 12c shows the performance of throughput vs. mobility, where $0 \leq Mo \leq 50$ km/h, with *Br* fixed at 4 time slots, *Bn* fixed at 25%, and *Se* fixed at 8. A higher throughput indicates a better scheme. The shoelace-based scheme has a better throughput than the other schemes. This is because the zone-disjoint scheme and flow-control scheme only guarantee the QoS requirement of high priority flow. The entire throughput of the network becomes lower due to other priority flows do not satisfy the QoS requirement. Figure 12d shows the performance of throughput vs. average network bandwidth, where $4 \leq Se \leq 12$, with *Mo* fixed at 30 km/h, *Br* fixed at 4 time slots, and *Bn* fixed at 25%. The shoelace scheme is better than the others and when the number of sector becomes greater, the throughput also becomes higher.

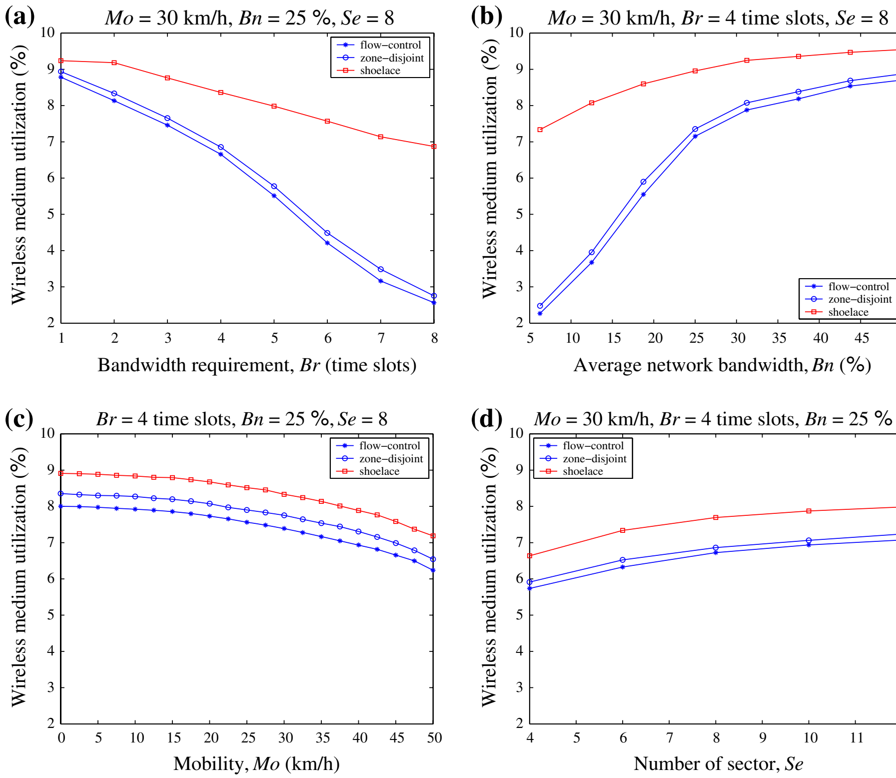

Fig. 13 Performance of (**a**) utilization vs. bandwidth requirement, (**b**) utilization vs. average usable network bandwidth, (**c**) utilization vs. mobility, (**d**) utilization vs. number of sector

5.3 Wireless Medium Utilization

The simulation results shown in Fig. 13 illustrate the performance of wireless medium utilization. The wireless medium utilization is obtained by calculating the number of received data packets for all destination hosts divided by the simulation area. Figure 13a shows the performance of wireless medium utilization vs. bandwidth requirement, where $1 \leq Br \leq 8$ time slots, with *Mo* fixed at 30 km/h, *Bn* fixed at 25%, and *Se* fixed at 8. When the bandwidth requirement is increased, the shoelace-based protocol is obvious better than the others. This is because the cross links of the shoelace scheme can simultaneously transmit data without any data interference. Figure 13b shows the performance of wireless medium utilization vs. average usable network bandwidth, where $6.25 \leq Bn \leq 50$ percentage, with *Mo* fixed at 30 km/h, *Br* fixed at 4 time slots, and *Se* fixed at 8. When the average network usable bandwidth is low, the shoelace scheme outperform the others. Figure 13c shows the performance of wireless medium utilization vs. mobility, where $0 \leq Mo \leq 50$ km/h, with *Br* fixed at 4 time slots, *Bn* fixed at 25%, and *Se* fixed at 8. A higher wireless medium utilization indicates a better scheme. The shoelace-based scheme has a better wireless medium utilization than the other schemes. This is because that our shoelace scheme allows overlapping link. Figure 13d shows the performance of wireless medium utilization vs. average network bandwidth, where $4 \leq Se \leq 12$, with *Mo* fixed at 30 km/h, *Br* fixed at 4 time slots, and *Bn* fixed at 25%.

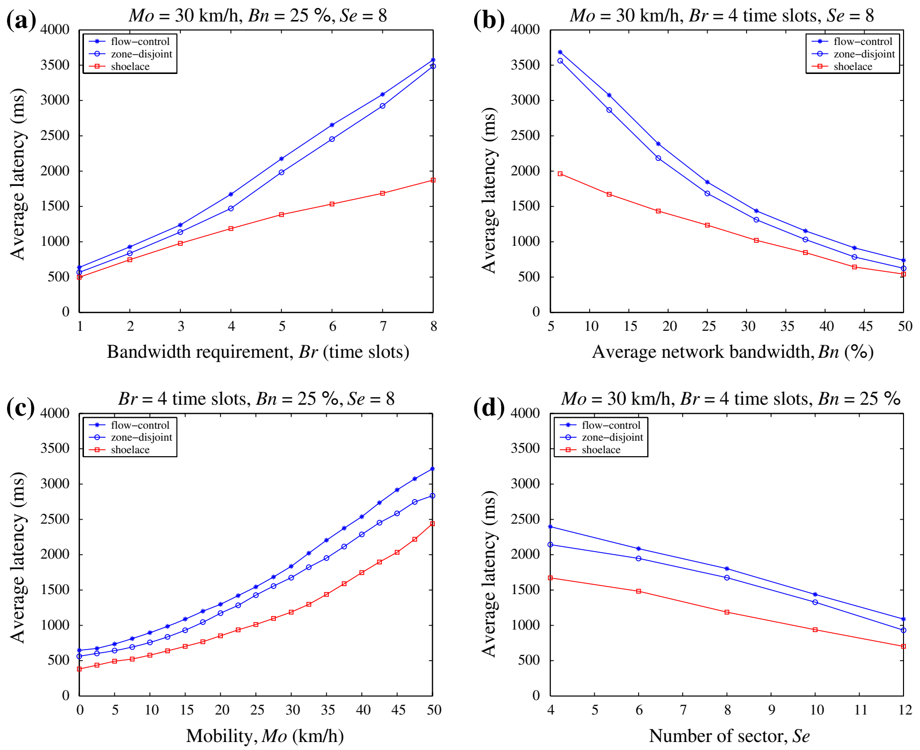

Fig. 14 Performance of (**a**) average latency vs. bandwidth requirement, (**b**) average latency vs. average usable network bandwidth, (**c**) average latency vs. mobility, (**d**) average latency vs. number of sector

When the number of sector becomes greater, the wireless medium utilization also becomes higher. This is because when the number of sector increases, the data interference decreases.

5.4 Average Latency

The simulation results shown in Fig. 14 illustrates the performance of average latency. The average latency is obtained by calculating the average of all the estimated latency. Figure 14a shows the performance of average latency vs. bandwidth requirement, where $1 \leq Br \leq 8$ time slots, Mo is 30 km/h, *Bn* is 25%, and *Se* is 8. The shoelace-based scheme has better average latency than the other schemes, even if the bandwidth requirement is high. This is because when the bandwidth requirement is high, the low priority flows of zone-disjoint scheme and flow-control scheme is more likely to block flow and reduce flow rate, respectively. Hence, the low priority flows bring higher average latency. Figure 14b shows the performance of average latency vs. average usable network bandwidth, where $6.25 \leq Bn \leq 50$ percentage, *Mo* is 30 km/h, *Br* is 4 time slots, and *Se* is 8. The shoelace scheme performs better than the other schemes when the average usable network bandwidth is strictly insufficient. This is because the shoelace scheme uses multi-path and cross link which simultaneously transmit data without any data interference. Figure 14c shows the performance of average latency vs. mobility, where $0 \leq Mo \leq 50$ km/h, *Br* is 4 time slots, *Bn* is 25%, and *Se* is 8. A lower average latency indicates a better performance. The shoelace-based scheme has a lower average

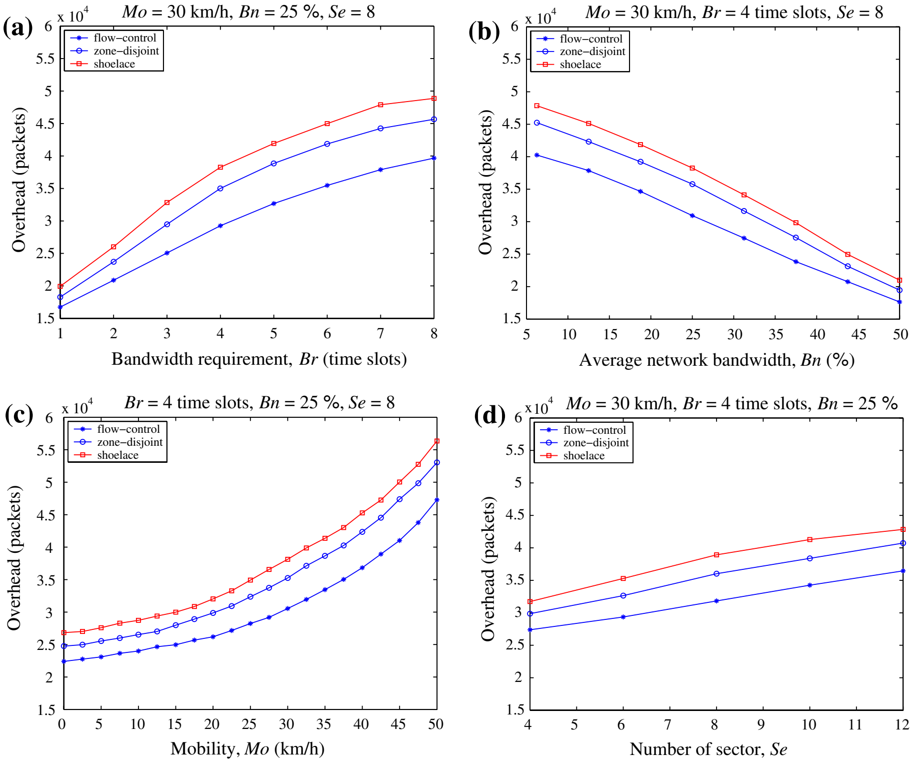

Fig. 15 Performance of (**a**) overhead vs. bandwidth requirement, (**b**) overhead vs. average usable network bandwidth, (**c**) overhead vs. mobility, (**d**) overhead vs. number of sector

latency than the other schemes. This is because that the cross links can transmit data simultaneously without interfering each other. Figure 14d shows the performance of average latency vs. number of sectors, where $4 \leq Se \leq 12$ time slots, Mo is 30 km/h, Br is 4 time slots, and Bn is 25%. The greater number of sector there is, the lower the average latency will be. This is because the greater number of sector has farther transmission range resulting in less hop counts.

5.5 Control Overhead

Figure 15 shows the performance of the control overhead under various parameters. Our approach aims to obtain a more stable QoS route, by adding some extra control overhead cost. Our scheme offers higher success rate, higher throughput, and lower average latency by increasing some extra control packets. Figure 15a shows the performance of control overhead vs. bandwidth requirement, where $1 \leq Br \leq 8$ time slots, Mo is 30 km/h, Bn is 25%, and Se is 8. The shoelace-based scheme acquires more number of control packets than the other schemes under the requirement of different bandwidth from one to eight time slots. However, the shoelace-based scheme can provide more stable QoS routes. Figure 15b shows the performance of control overhead vs. average usable network bandwidth, where $6.25 \leq Bn \leq 50$ percentage, Mo is 30 km/h, Br is 4 time slots, and Se is 8. The shoelace scheme acquires more overheads than the other schemes under different average usable network bandwidth from 6.25 to 50%. Figure 15c shows the performance of control overhead vs. mobility, where $0 \leq Mo \leq 50$ km/h, *Br* is 4 time slots, *Bn* is 25%, and *Se* is 8. A lower overhead indicates a better scheme. The shoelace-based scheme has higher control overhead than the others. This is because the shoelace-based scheme needs to find other sub-paths to satisfy the QoS requirement. Figure 15d shows the performance of control overhead vs. number of sector, where $4 \leq Se \leq 12$, *Mo* is 30 km/h, *Br* is 4 time slots, and *Bn* is 25%. The greater number the sector is, the more the overhead will be. This is because the nodes need more time to switch its sector to find all neighbors.

6 Conclusions

We have proposed a new QoS routing protocol which is based on the concept of multi-path, namely shoelace-based QoS routing protocol, for mobile ad hoc network using directional antennas, where the MAC sub-layer adapts the CDMA-over-TDMA channel model. These cross links can simultaneously transmit data without any data interference. Our scheme provides an on-demand dynamic routing path according to the network bandwidth. The shoelace-based route is a uni-path if the network bandwidth is sufficient and a multi-path if the network bandwidth is insufficient. The performance results reflect that the shoelace-based scheme presents better result when the network bandwidth is strictly insufficient. Our shoelace-based scheme improves the success rate, throughput, and average latency. Performance results demonstrate that the proposed protocol outperforms the existing QoS routing protocol, which uses directional antennas.

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