PAPER

A Lantern-Tree-Based QoS On-Demand Multicast Protocol for a Wireless Mobile Ad Hoc Network*

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SUMMARY The multimedia applications have recently generated much interest in wireless network infrastructure with supporting the quality-of-service (QoS) communications. In this paper, we propose a lantern-tree-based QoS on-demand multicast protocol for wireless ad hoc networks. Our proposed scheme offers a bandwidth routing protocol for QoS support in a multihop mobile network, where the MAC sub-layer adopts the CDMA-over-TDMA channel model. The QoS on-demand multicast protocol determines the end-to-end bandwidth calculation and bandwidth allocation from a source to a group of destinations. In this paper, we identify a lantern-tree for developing the QoS multicast protocol to satisfy certain bandwidth requirement, while the lantern-tree is served as the multicast-tree. Our lantern-tree-based scheme offers a higher success rate to construct the QoS multicast tree due to using the lantern-tree. The lantern-tree is a tree whose sub-path is constituted by the lantern-path, where the lantern-path is a kind of multi-path structure. This obviously improves the success rate by means of multi-path routing. In particular, our proposed scheme can be easily applied to most existing on-demand multicast protocols. Performance analysis results demonstrate the achievements of our proposed protocol.

key words: *CDMA-over-TDMA, mobile ad hoc network, quality-of-service (QoS), multicast, multi-path, wireless network*

1. Introduction

Mobile ad hoc networks (MANETs) [10], [13], [14], [21], [23], [24] consist of wireless hosts that communicate with each other in the absence of a fixed infrastructure. In a MANET, host mobility can cause frequent unpredictable topology changes, thus the design of a MANET QoS routing protocol is more complicated than that of traditional networks because it requires strong fault-tolerant capabilities. Since a MANET is characterized by its fast changing topology, extensive research efforts have been devoted to the design of routing protocols for MANETs [5], [7]. These protocols, when searching for a route to a destination, are concerned with shortest-path routing and the availability of multiple routes in the MANET's dynamically changing environment.

Some work has recently intensively studied QoS issues in MANETs. These problems have been addressed in several studies in the literature [3], [4], [9], [11]–[13], [15]–[18], [20]–[22], [24]. Initially, in a quite ideal model, it is assumed that the bandwidth of a link can be determined on its neighboring links [3]. This strong assumption may be realized by a costly multi-antenna model such that a host can send/receive using different antennas independently and simultaneously. Under such a model, a ticket-based QoS routing protocol was proposed in [3]. Using the same model, Liao et al. recently proposed a QoS multi-path routing protocol [15]. Observe that Liao et al.'s routing protocol presents a multi-path concept to satisfy bandwidth constraints. A CDMA-over-TDMA channel model was recently assumed in [16], [17] to develop a QoS routing protocol in a MANET, where the use of a time slot on a link is only dependent on the status of its one-hop neighboring links. Based on such a model, Lin and Liu calculated the end-to-end path bandwidth to develop DSDV-based QoS routing [17] and on-demand QoS routing [16] in a MANET. More recently, Chen et al. [8] develop an on-demand, link-state, multi-path QoS routing protocol in a wireless mobile ad-hoc network. This protocol collects link bandwidth information from source to destination in order to construct a network topology with the information of link bandwidth at the destination. The bandwidth calculation of the QoS route is determined at the destination. In general, "bandwidth" in time-slotted network system is measured in terms of the amount of "free" slots. The goal of the QoS multicast routing protocol is searching for a multicast tree from a source to all destinations such that the total bandwidth on these available paths of the multicast tree are above the minimal requirement. To computer the "bandwidth"-constrained paths from source to destinations, we not only have to know the available bandwidth on each link along all possible paths of the multicast tree, but we also have to do a suitable scheduling of free slots.

The multicast protocol is a primitive communication operation for sending the same message from a source node to a group of destination nodes. It is very significant for many mobile applications; for example, a mobile learning system for bird watching in [6] and mobile learning system for ad hoc classroom in [2] offer the QoS multicast service to the bird watching learners or students in a mobile ad hoc classroom. There are many existing MANET multicast protocols, such as CBT [10], AODV [21], DVMRP [9], CAMP [19], FGMP [23], ODMRP [14], and SOM [5] protocols. However, these multicast protocols do not provide the QoS function. The design difficulty of designing QoS multicast protocols in a MANET is greater than for tradi-

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tional MANET multicast protocols due to the need to take bandwidth-reservation into consideration. Efforts are made in this paper to develop a QoS on-demand multicast protocol in a MANET.

In this paper, we propose a lantern-tree-based QoS multicast protocol with a reliable mechanism for MANETs, where the MAC sub-layer adopts the well-known CDMA-over-TDMA channel model [16], [17]. Under such a model, we identify a lantern-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. In addition, our protocol also offers a simple reliable mechanism to guarantee reliable communications. In this work, the lantern-tree serves as the multicast-tree. Our lantern-tree-based scheme offers a higher success rate for constructing the QoS multicast tree due to using the lantern-tree. The lantern-tree is a multicast tree whose sub-paths comprise the lantern-path. The lantern-path is a special multi-path structure. This greatly improves the success rate by means of multi-path routing. In particular, our proposed scheme can be directly applied to most existing on-demand multicast protocols. Performance analysis results demonstrate the achievements of our proposed protocol.

The rest of this paper is organized as follows. Section 2 presents the basic ideas and challenges of our multicast protocol. Our protocol is presented in Sect. 3. Section 4 shows the simulation results. Finally, Sect. 5 concludes this paper.

2. Basic Idea and Challenges

This paper mainly introduces and identifies a special multicast tree structure, namely a *lantern-tree*, from a source to a set of destination nodes which satisfies a given bandwidth requirement. The CDMA-over-TDMA channel model is assumed to follow the same model as defined in [16], [17]. The CDMA (code division multiple access) is overlaid on top of the TDMA infrastructure. Multiple sessions can share a common TDMA slot via CDMA. Observe that, under such a model, the use of a time slot on a link is only dependent on the status of its one-hop neighboring links. This model may be emulated by wireless LAN cards which follow the IEEE 802.11 standard [1]. Each data phase of a TDMA frame is assumed to be partitioned into κ time slots.

In the following, we introduce the terms *lantern*, *lantern-path,* and *lantern-tree*. In this paper, a QoS path is a path which satisfies a given bandwidth requirement under the CDMA-over-TDMA channel model from a source to a destination node. Initially, the lantern is defined. A lantern is a special structure of the multi-path. A path is a lantern-path if each component of the path may be a lantern or a uni-path. A lantern-tree is eventually constructed, where the path of a multicast tree comprises the lantern-path. The lantern-tree is constructed for the purpose of increasing the success rate of the tree searching and promoting stability of the tree maintenance. Consider a pair of two-hop neighbor nodes A and B; a QoS path is requested between nodes A to B which satisfies a bandwidth requirement B_r as shown in Fig. 1(a).

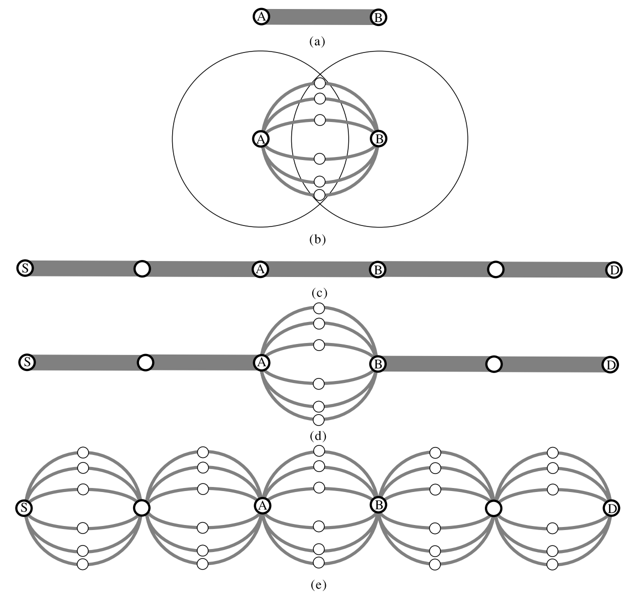


Fig. 1 Examples of (a) a link, (b) lantern, (c) path, (d) lantern-path, and (e) worst-case situation of a lantern-path.

Definition 1: Lantern: Given a pair of two-hop neighboring nodes A and B, one or more sub-paths exist between A and B, and the total bandwidth of one or more sub-paths is equal to B_r. One or more sub-paths and the total bandwidth B_r are denoted as a lantern.

Figure 1(b) shows a lantern. Each sub-path in a lantern is responsible for a sub-bandwidth requirement. The number of sub-paths of a lantern is dependent on the network bandwidth. The value of the lantern is in its flexibility: (i) when the network bandwidth is strictly limited, the lantern offers a multi-path routing as illustrated in Fig. 1 (b), and (ii) when the network bandwidth is sufficient, the lantern only provides a uni-path routing as illustrated in Fig. 1(a). The nature of the lantern is to increase the success rate of identifying a QoS route and providing a robust and reliable mechanism. Continuing, consider a QoS path requested from node S to node D which satisfies the bandwidth requirement B_r as given in Fig. 1(c). An alterative path from S to D, namely the *lantern-path*, can be constructed, where the components of the path are lanterns. The lantern-path inherits the advantage of a high success rate of searching for a QoS route and the robust and reliable mechanisms from the nature of the lantern.

Definition 2: Lantern-path: A path is said as a lantern-path if one or more lanterns exist in the path.

For instance as illustrated in Fig. 1(d), only one lantern exists in the path. Five lanterns occur in the path as shown in Fig. 1(e). Each lantern in the lantern-path is viewed as a multi-path routing. Comparing Fig. 1(d) with Fig. 1(e), the path in Fig. 1(d) indicates that a QoS uni-path, from S to D, is available except for the sub-paths from A to B. In the

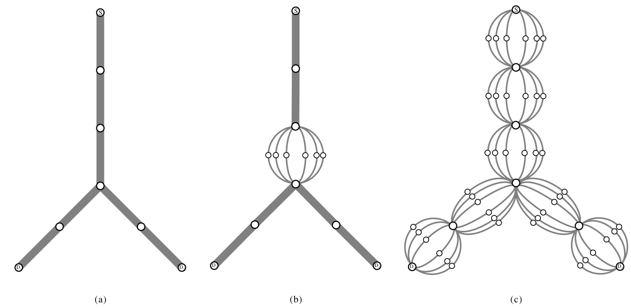


Fig. 2 Examples of (a) a conventional-tree, (b) lantern-tree, and (c) worst-case situation of a lantern-tree.

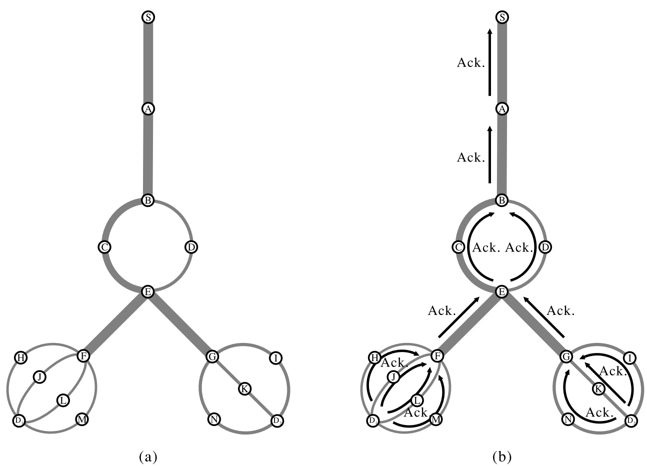


Fig. 3 Examples of (a) a lantern-tree and (b) a lantern-tree with a reliable mechanism.

worse case, if we cannot search for a uni-path from S to D, a lantern-path with a greater number of lanterns is identified. A lantern-path with a fewer number of lanterns will be recognized if the network bandwidth is sufficient. A lantern-path with a greater number of lanterns will be constructed if the network bandwidth is limited. This paper presents a new multicast tree structure, namely the *lantern-tree*. The lantern-tree is a tree whose path is the lantern-path.

Definition 3: Lantern-tree: A tree is denoted a lantern-tree if the path of the tree is replaced by the lantern-path.

For example, Fig. 2(a) shows a tree, and Fig. 2(b) and Fig. 2(c) are examples of lantern-trees with different numbers of lanterns. Similarly, a lantern-tree with a fewer number of lantern is recognized if the network bandwidth is sufficient as shown in Fig. 2(b). A lantern-tree with a greater number of lanterns is constructed if the network bandwidth is limited as illustrated in Fig. 2(c). In summary, the advantage of the proposed lantern-tree is (1) *task sharing*: each sub-path of a lantern-tree is responsible for the partial bandwidth requirement; and (2) *high stability capability:* Each sub-path of a lantern is responsible for the less number of bandwidth requirements. It is more easier to search for a backup sub-path with the less number of bandwidth requirement to keep the lantern structure if one sub-path of a lantern is failed. Therefore, this approach more easily maintains the QoS-route stability than any existing QoS uni-path routing results.

In addition, the proposed lantern-tree offers a reliable mechanism to provide a reliable multicast transmission. The reliable mechanism is accomplished by adding the ACK.. short message within each lantern of the lantern-tree. Figure 3(a) is a lantern-tree and Fig. 3(b) shows a lantern-tree with a reliable mechanism.

3. LTM: Lantern-Tree-Based QoS Multicast Protocol

We first provide an overview of our proposed LTM: Lantern-Tree-based QoS Multicast routing protocol. The LTM protocol mainly constructs a lantern-tree to perform the on-demand QoS multicast routing operation. The LTM protocol is achieved by the three phases of *lantern identification, lantern-tree construction* and *lantern-tree maintenance*. The *lantern identification* phase identifies the lantern for each node in a MANET. The *lantern-tree construction* phase constructs the lantern-tree by merging lantern-paths from a source to all destinations. The *lantern-tree maintenance* phase maintains the lantern-tree structure for the sake of enhancing the robustness and preserving its stability.

3.1 Phase 1: Lantern Identification

To identify the lantern, local link-state information is collected for each node in the MANET. This work is accomplished by periodically maintaining the beacon message, where the beacon lifetime is two-hop. Since the beacon message floods into MANET within two-hops, each node acquires local link-state information from all two-hop neighboring nodes before identifying the lantern.

A free time slot list is denoted as $\{\alpha_1, \alpha_2, \cdots, \alpha_\kappa\}$, where $\alpha_1, \alpha_2, \cdots, \alpha_\kappa$ comprise a set of free time slots. The link-state information includes all one-hop and two-hop neighboring nodes and all corresponding free time slot list of these nodes. For instance as shown in Fig. 4(a), one-hop neighboring node of A is B, and the free time slot list of B is $\{3, 4, 5, 6, 7, 8\}$, while the two-hop neighboring node of A is E, and the free time slot list of E is $\{1, 3, 4, 5, 6\}$. If free time slot lists of two neighboring nodes A and B are $\{\alpha_1, \alpha_2, \cdots, \alpha_{\kappa_1}\}$ and $\{\beta_1, \beta_2, \cdots, \beta_{\kappa_2}\}$, we use an intersection function $\cap(\{\alpha_1, \alpha_2, \cdots, \alpha_{\kappa_1}\}, \{\beta_1, \beta_2, \cdots, \beta_{\kappa_2}\}) = (\gamma_1, \gamma_2, \cdots, r_{\kappa_3})$, where $\kappa_3 \leqq \min\{\kappa_1, \kappa_2\}$. Let $(\gamma_1, \gamma_2, \cdots, r_{\kappa_3})$ represent the shared free time slots between nodes A and B. This indicates that communication between A and B should be selected from shared free time slots $(\gamma_1, \gamma_2, \cdots, r_{\kappa_3})$. For example as shown in Fig. 4(a), the free time slot lists of A and B are $\{1, 2, 4, 7, 8\}$ and $\{3, 4, 5, 6, 7, 8\}$, respectively, so $\cap(\{1, 2, 4, 7, 8\}, \{3, 4, 5, 6, 7, 8\}) = (4, 7, 8)$ as illustrated in Fig. 4(a). Observe that, after free time slots are calculated in a link between two nodes, the time slots will be reserved and the time slots won't be able to use when free time slots will be calculated at the next link. For instance, time slots $(4, 7, 8)$ are calculated in link between nodes A and B, then

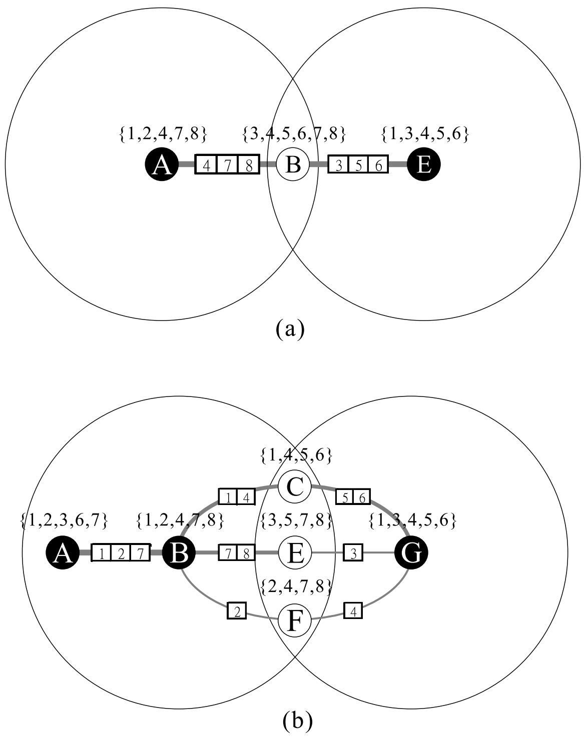


Fig. 4 Identifying the lantern and its link bandwidth.

time slots $(3, 5, 6)$ are reserved to link between nodes B and E.

The lantern is identified after collecting the local link-state information for all nodes in the MANET. Given a pair of two-hop neighboring nodes e and e', if one or more disjoint sub-paths exist from e to e', then a lantern is constructed between e and e'. A counterexample shows that a lantern does not exist from node A as illustrated in Fig. 4(b), although there are many sub-paths from A. Denote $[n_1, n_2, \cdots, n_k]$ as a path from node n_1 to node n_k, and $[n_1, n_2]$ as a link connecting n_1 and n_2. From the table illustrated in Fig. 4(a), three disjoint sub-paths $[B, C, G]$, $[B, E, G]$, and $[B, F, G]$ exist between B and G, and a lantern occurs from B to G. Let $\begin{bmatrix} & n_1 & \\ \alpha & \vdots & \beta \\ & n_k & \end{bmatrix}$ denote a lantern between α and β, where $[\alpha, n_1, \beta]$, $\cdots$, and $[\alpha, n_k, \beta]$ are k disjoint sub-paths between α and β. For example as shown in Fig. 4(b), $\begin{bmatrix} & C & \\ B & E & G \\ & F & \end{bmatrix}$ is a lantern. Further, free time slot lists of B, C, E, F, and G are known from the local link-state information. The shared time slot list on link $[n_1, n_2]$ is denoted as $S[n_1, n_2] = \cap(\{\alpha_1, \alpha_2, \cdots, \alpha_{\kappa_1}\}, \{\beta_1, \beta_2, \cdots, \beta_{\kappa_2}\})$, where free time slot lists of n_1 and n_2 are $\{\alpha_1, \alpha_2, \cdots, \alpha_{\kappa_1}\}$ and $\{\beta_1, \beta_2, \cdots, \beta_{\kappa_2}\}$, respectively. Therefore, $S[B, C] = (1, 4)$, $S[B, E] = (7, 8)$, $S[B, F] = (2)$, $S[C, G] = (5, 6)$, $S[E, G] = (3)$, and $S[F, G] = (4)$. The number of shared time slots of $S[n_1, n_2]$ is denoted as $|S[n_1, n_2]|$. For example, $|S[B, C]| = 2$, $|S[B, E]| = 2$, $|S[B, F]| = 1$, $|S[C, G]| = 2$, $|S[E, G]| = 1$, and $S[F, G]| = 1$, as shown in Fig. 4(b).

We further denote $\begin{bmatrix} & n_1(sn_1) & \\ \alpha & \vdots & \beta \\ & n_k(sn_k) & \end{bmatrix}$ as a lantern between α and β, where sn_i denotes the maximum number of reserved time slots for sub-path $[\alpha, n_i, \beta]$. Following the above example, a lantern $\begin{bmatrix} & C(2) & \\ B & E(1) & G \\ & F(1) & \end{bmatrix}$ is identified for node B, and the maximum number of reserved time slots of the lantern $\begin{bmatrix} & C & \\ B & E & G \\ & F & \end{bmatrix}$ is four. This information is useful for constructing a lantern-path as described below. Observe that, lantern $\begin{bmatrix} & n_1(sn_1) & \\ \alpha & \vdots & \beta \\ & n_k(sn_k) & \end{bmatrix}$ can be a uni-path $[\alpha\ \gamma(sn)\ \beta]$ if a uni-path exists, where $sn = \sum_{i=1}^{k} sn_i$. This indicates that the lantern identification is dependent on the network bandwidth. If the network bandwidth is sufficient, then a $[\alpha\ \gamma(sn)\ \beta]$ is identified. Otherwise, a lantern $\begin{bmatrix} & n_1(sn_1) & \\ \alpha & \vdots & \beta \\ & n_k(sn_k) & \end{bmatrix}$ is constructed if the network bandwidth is limited.

Since the MAC sub-layer adopts the CDMA-over-TDMA channel model [16], [17], the time slot reservation of $\begin{bmatrix} & n_1(sn_1) & \\ \alpha & \vdots & \beta \\ & n_k(sn_k) & \end{bmatrix}$ has the following rules.

(r1) Time-slot reserves on link $[\alpha\ n_i(sn_i)]$ and $[n_i(sn_i)\ \beta]$ must differ, where $1 \leqq i \leqq k$.
(r2) Time-slot reserves on link $[\alpha\ n_i(sn_i)]$ and $[n_j(sn_j)\ \beta]$ can be the same, where $1 \leqq i \neq j \leqq k$.
(r3) Time-slot reserves on all links $[\alpha\ n_i(sn_i)]$ must differ, for $1 \leqq i \leqq k$.
(r4) Time-slot reserves on all links $[n_i(sn_i)\ \beta]$ must differ, where $1 \leqq i \leqq k$.

An instance of the time-slot reservation is given in Fig. 4(b).

(r1) Time slots $(1, 4)$ on link $[B, C]$ differ from slots $(5, 6)$ on link $[C, G]$.
(r2) Time slot (4) on link $[B, C]$ is the same as slot (4) on link $[F, G]$.
(r3) Time slots $(1, 4), (7, 8)$, and (2) on links $[B, C], [B, E]$, and $[B, F]$ differ.
(r4) Time slots $(5, 6), (3)$, and (4) on links $[C, G], [E, G]$, and $[F, G]$ differ.

This time-slot reservation is used as the primitive operation to construct the lantern-path and lantern-tree as follows.

3.2 Phase 2: Lantern-Tree Construction

The lantern-tree construction phase is divided into two operations.

1) *The Lantern-Path Search Operation*: Based on the identified lanterns, many lantern-paths from a source to a given set of destinations are constructed.
2) *The Lantern-Path with a Reliable Mechanism:* A lantern-path with a reliable mechanism is provided.
3) *The Lantern-Tree Construction Operation*: Based on multiple lantern-paths, a lantern-tree is established.
4) *The Lantern-Tree with a Reliable Mechanism:* A lantern-tree with a reliable mechanism is provided.

These three operations are described as follows.

3.2.1 The Lantern-Path Search Operation

Let $\left[\left[\begin{matrix} & n_{1,1}(sn_{1,1}) & \\ \alpha_1 & \vdots & \beta_1 \\ & n_{1,k_1}(sn_{1,k_1}) & \end{matrix}\right], \cdots, \left[\begin{matrix} & n_{j,1}(sn_{j,1}) & \\ \alpha_j & \vdots & \beta_j \\ & n_{j,k_j}(sn_{j,k_j}) & \end{matrix}\right]\right]$ denote a lantern-path, where $\left[\begin{matrix} & n_{i,1}(sn_{i,1}) & \\ \alpha_i & \vdots & \beta_i \\ & n_{i,k_i}(sn_{i,k_i}) & \end{matrix}\right]$ is the i-th lantern of the lantern-path, $\beta_i = \alpha_{i+1}$, and $1 \leqq i \leqq j-1$. Observe that $k_i \geqq 1$ and the i-th lantern can be a uni-subpath only if $k_i = 1$. The search lantern-path operation is given.

(A1) A source node initiates and floods a lantern-path request packet into the MANET to check if one or more lanterns exist for the source node. If a lantern exists, then a lantern path with one lantern $\left[\left[\begin{matrix} & n_{1,1}(sn_{1,1}) & \\ \alpha_1 & \vdots & \beta_1 \\ & n_{1,k_1}(sn_{1,k_1}) & \end{matrix}\right]\right]$ is constructed. An instance is given in Fig. 5 where lantern-path $\left[\left[S \begin{matrix} A(2) \\ B(1) \end{matrix} C\right]\right]$ is constructed.

(A2) We repeatedly perform step *A1* until a possible lantern-path arrives at a destination node, then a lantern-path $\left[\left[\begin{matrix} & n_{1,1}(sn_{1,1}) & \\ \alpha_1 & \vdots & \beta_1 \\ & n_{1,k_1}(sn_{1,k_1}) & \end{matrix}\right], \cdots, \left[\begin{matrix} & n_{j,1}(sn_{j,1}) & \\ \alpha_j & \vdots & \beta_j \\ & n_{j,k_j}(sn_{j,k_j}) & \end{matrix}\right]\right]$ is constructed. The lantern-path $\left[\left[\begin{matrix} & n_{1,1}(sn_{1,1}) & \\ \alpha_1 & \vdots & \beta_1 \\ & n_{1,k_1}(sn_{1,k_1}) & \end{matrix}\right], \cdots, \left[\begin{matrix} & n_{j,1}(sn_{j,1}) & \\ \alpha_j & \vdots & \beta_j \\ & n_{j,k_j}(sn_{j,k_j}) & \end{matrix}\right]\right]$ is identified if the network bandwidth is limited. Figure 5 shows a lantern-path $\left[\left[S \begin{matrix} A(2) \\ B(1) \end{matrix} C\right], [C\ E(3)\ F], \left[F \begin{matrix} G(1) \\ H(1) \\ I(1) \end{matrix} D\right]\right]$. On the contrary, if the network bandwidth is sufficient, the construction of the i-th lantern $\left[\begin{matrix} & n_{i,1}(sn_{i,1}) & \\ \alpha_i & \vdots & \beta_i \\ & n_{i,k_i}(sn_{i,k_i}) & \end{matrix}\right]$ is given as follows.

(B1) The i-th lantern $\left[\begin{matrix} & n_{i,1}(sn_{i,1}) & \\ \alpha_i & \vdots & \beta_i \\ & n_{i,k_i}(sn_{i,k_i}) & \end{matrix}\right]$ can be a two-hop uni-path $[\alpha_i\ \gamma_i(sn_i)\ \beta_i]$ if $sn_i = \sum_{t=1}^{k_i} sn_{i,t}$. This condition occurs if the network bandwidth, from α_i through γ_i to β_i, is sufficient.

(B2) The i-th lantern $\left[\begin{matrix} & n_{i,1}(sn_{i,1}) & \\ \alpha_i & \vdots & \beta_i \\ & n_{i,k_i}(sn_{i,k_i}) & \end{matrix}\right]$ can be a one-hop uni-path $[\alpha_i\ \beta_i]$ if the link bandwidth of $[\alpha_i\ \beta_i]$ is $\sum_{t=1}^{k_i} sn_{i,t}$. This condition occurs if the network bandwidth between α_i and β_i is sufficient.

Observe that if all lanterns of lantern path $\left[\left[\begin{matrix} & n_{1,1}(sn_{1,1}) & \\ \alpha_1 & \vdots & \beta_1 \\ & n_{1,k_1}(sn_{1,k_1}) & \end{matrix}\right], \cdots, \left[\begin{matrix} & n_{j,1}(sn_{j,1}) & \\ \alpha_j & \vdots & \beta_j \\ & n_{j,k_j}(sn_{j,k_j}) & \end{matrix}\right]\right]$ satisfy B1 and B2 conditions, then our resulting QoS route is the same as the result of Lin's hop-by-hop reservation scheme [16], [17]. That is, if the network bandwidth is sufficient, our result is the same as the well-known hop-by-hop reservation scheme [16], [17]. If the network bandwidth is limited, Lin's approach fails to search for a QoS route, but our lantern-path approach can successfully identify a QoS route. These important effects are discussed in Sect. 4. An example is shown in Fig. 6.

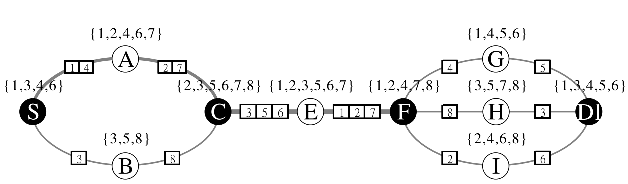


Fig. 5 Construction of a lantern-path.

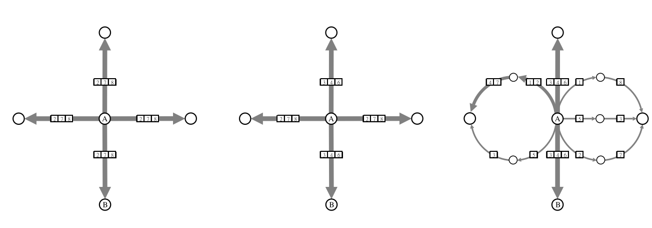


Fig. 6 Time-slot reservation when searching for a lantern-tree.

3.2.2 The Lantern-Path with a Reliable Mechanism

Considering a lantern path $\left[\begin{bmatrix} & n_{1,1}(sn_{1,1}) & \\ \alpha_1 & \vdots & \beta_1 \\ & n_{1,k_1}(sn_{1,k_1}) & \end{bmatrix}, \cdots, \begin{bmatrix} & n_{j,1}(sn_{j,1}) & \\ \alpha_j & \vdots & \beta_j \\ & n_{j,k_j}(sn_{j,k_j}) & \end{bmatrix}\right]$, we can add a simple reliable mechanism to the lantern path. For each $\begin{bmatrix} & n_{i,1}(sn_{i,1}) & \\ \alpha_i & \vdots & \beta_i \\ & n_{i,k_i}(sn_{i,k_i}) & \end{bmatrix}$ of the lantern-path, node α_i transmits messages to node β_i under the bandwidth requirement $\sum_{t=1}^{k_i} sn_{i,t}$. Observe that a simple ACK.. message must be sent from node β_i and received by node α_i, where $1 \leqq i \leqq k$. If each lantern of the lantern-path guarantees its successful transmission, then our lantern-path guarantees the successful transmission.

3.2.3 The Lantern-Tree Construction Operation

This paper mainly constructs a multicast tree modified from the spiral-fat-tree on-demand multicast (SOM) protocol [5]. Observe that the construction of our multicast tree can use the results of CBT [10], AODV [21], DVMRP [9], CAMP [19], FGMP [23], and ODMRP [14]. In this work, all spiral-paths of the spiral-fat-tree [5] are replaced by a lantern-path for the purpose of providing QoS capability. An example of a lantern-tree is illustrated in Fig. 7(a).

Let $[l_1, l_2, \cdots, l_j](b)$ represent lantern-path $\left[\begin{bmatrix} & n_{1,1}(sn_{1,1}) & \\ \alpha_1 & \vdots & \beta_1 \\ & n_{1,k_1}(sn_{1,k_1}) & \end{bmatrix}, \cdots, \begin{bmatrix} & n_{j,1}(sn_{j,1}) & \\ \alpha_j & \vdots & \beta_j \\ & n_{j,k_j}(sn_{j,k_j}) & \end{bmatrix}\right]$, where $l_i = \begin{bmatrix} & n_{i,1}(sn_{i,1}) & \\ \alpha_i & \vdots & \beta_i \\ & n_{i,k_i}(sn_{i,k_i}) & \end{bmatrix}$ is the i-th lantern of the lantern-path, and bandwidth $b = \sum_{t=1}^{k_i} sn_{i,t}$. Given that two lantern-paths $[l_1, l_2, \cdots, l_p, l_{p+1}, \cdots, l_k](b)$ and $[l_1, l_2, \cdots, l_p, l'_{p+1}, \cdots, l'_k](b)$ have the same lantern sub-path $[l_1, l_2, \cdots, l_p](b)$, we denote $\cap([l_1, l_2, \cdots, l_p, l_{p+1}, \cdots, l_k](b), [l_1, l_2, \cdots, l_p, l'_{p+1}, \cdots, l'_k](b)) = [l_1, l_2, \cdots, l_p](b)$. Further, let $[l_1, l_2, \cdots, l_p]$ (b, s) denote s lantern-paths with the same $[l_1, l_2, \cdots, l_p]$ (b). We also denote $\|[l_1, l_2, \cdots, l_p](b)\| = p$ to be the number of lanterns, which indicates the number of shared lantern sub-paths for a given s lantern-paths. Given each pair of s and s' replying lantern-paths, among many replying lantern-paths from destination nodes to the source node, we have the merging criterion to construct the lantern-tree according to the values of p, s, and b.

(C1) If the s replying lantern-paths have maximum values of p, s, and b, then these s lantern-paths are merged together with the highest priority.

(C2) If there are s and s' replying lantern-paths with the same values of p and s, then s lantern-paths with the greater value of b are merged together.

(C3) If there are s and s' replying lantern-paths with the same values of b and s, then s lantern-paths with the greater value of p are merged together.

(C4) If there are s and s' replying lantern-paths with the same values of b and p, then s lantern-paths with the greater value of s are merged together.

(C5) If there are s and s' replying lantern-paths with the same values of p, then s lantern-paths with the greater value of b are merged together.

(C6) If there are s and s' replying lantern-paths with the same values of s, then s lantern-paths with the greater value of b are merged together.

(C7) If there are s and s' replying lantern-paths with the same values of b, then s lantern-paths with the greater value of s are merged together.

(C8) If there are s and s' replying lantern-paths with different values for p, b, and s, then s lantern-paths with the greater value of b are merged together.

Figure 8(a) and Fig. 8(b) provide an example of case ($C6$), and Fig. 8(b) and Fig. 8(c) provide an instance of case ($C7$).

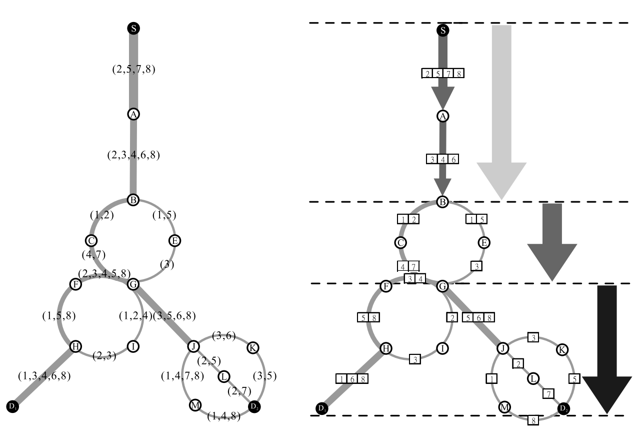


Fig. 7 Details of time-slot reservation for identifying a lantern-tree.

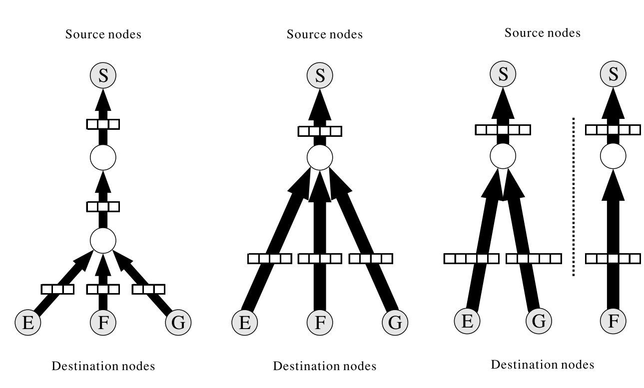


Fig. 8 The lantern-tree merging criterion.

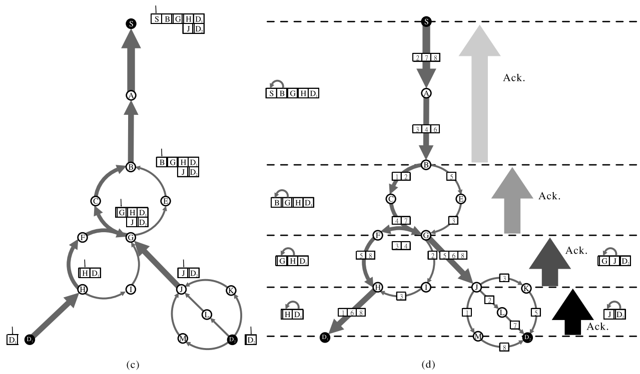


Fig. 9 Example of a lantern-tree with a reliable mechanism.

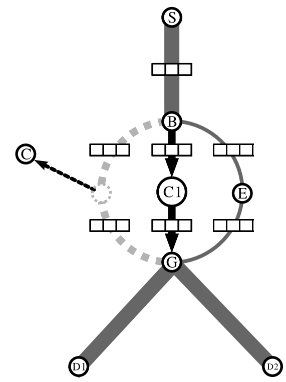


Fig. 10 Example of lantern-tree maintenance.

3.2.4 The Lantern-Tree with a Reliable Mechanism

Consider a lantern-tree where each lantern $\begin{bmatrix} & n_{i,1}(sn_{i,1}) & \\ \alpha_i & \vdots & \beta_i \\ & n_{i,k_i}(sn_{i,k_i}) & \end{bmatrix}$ performs a simple reliable mechanism. Node α_i transmits messages to node β_i under the bandwidth requirement $\sum_{t=1}^{k_i} sn_{i,t}$. Observe that a simple Ack. message must be sent from node β_i and received by node α_i, where $1 \leqq i \leqq k$. If each lantern of the lantern-tree guarantees its successful transmission, then the lantern-tree guarantees the successful transmission. An example is illustrated in Fig. 9.

3.3 Phase 3: Lantern-Tree Maintenance

Given a lantern path $\left[\begin{bmatrix} & n_{1,1}(sn_{1,1}) & \\ \alpha_1 & \vdots & \beta_1 \\ & n_{1,k_1}(sn_{1,k_1}) & \end{bmatrix}, \cdots, \begin{bmatrix} & n_{j,1}(sn_{j,1}) & \\ \alpha_j & \vdots & \beta_j \\ & n_{j,k_j}(sn_{j,k_j}) & \end{bmatrix}\right]$, if $\begin{bmatrix} & n_{i,1}(sn_{i,1}) & \\ \alpha_i & \vdots & \beta_i \\ & n_{i,k_i}(sn_{i,k_i}) & \end{bmatrix}$ is the i-th lantern of the lantern-path and sub-path $[\alpha_i \ n_{i,t}(sn_{i,t}) \ \beta_i]$ fails, then we try to search for a backup sub-path $[\alpha_i \ b(sn_{i,t}) \ \beta_i]$ to replace the failed sub-path $[\alpha_i \ n_{i,t}(sn_{i,t}) \ \beta_i]$. An example is shown in Fig. 10 in which lantern $\begin{bmatrix} B & \begin{matrix} C(3) \\ E(3) \end{matrix} & G \end{bmatrix}$ is replaced by lantern $\begin{bmatrix} B & \begin{matrix} C_1(3) \\ E(3) \end{matrix} & G \end{bmatrix}$ if node C is no longer available. When the QoS requirement could not be satisfied even using the proposed LTM for the dynamical topology changes, the lantern-tree maintenance phase will start its maintenance operation to maintain a lantern-tree structure for the dynamical topology changes. If it can maintain a lantern-tree structure, the real-time data transmission will be continued. If it cannot maintain the lantern-tree structure, the real-time data transmission will be stopped.

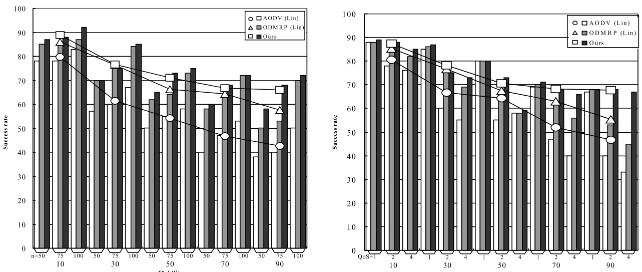
4. Experimental Results

We have developed a simulator which is done by C++ program. To examine the effectiveness of our approach, two well-known on-demand QoS multicast protocols, AODV [21] and ODMRP [14], are mainly compared with our approach. Observe that, AODV [21] and ODMRP [14] do not provide the QoS capability. In addition, Lin designed an on-demand QoS routing protocol in [16]. To make a fair comparison, we offer the QoS-extension AODV [21] and ODMRP [14] protocols such that each path in the AODV [21] and ODMRP [14] protocols adopts Lin's QoS unipath routing [16], where MAC sub-layer is adopted the CDMA-over-TDMA channel model. In this simulation, these two integrated results are denoted as AODV(Lin) and ODMRP(Lin), respectively. The simulation parameters are given below.

- The *mobility speed* is from 10 to 90 km/h.
- The *message length* ranges from 1 to 30 Kb.
- The *transmission radius* is from 50 to 150 m.
- The *number of mobile hosts* ranges 50, 75, and 100.
- The *bandwidth requirements* are 1, 2 and 4 time slots.
- The *number of time slots* in the data phase of a frame is assumed to be 16 slots.
- Each simulated result is obtained by averaging values through 5000 runs.

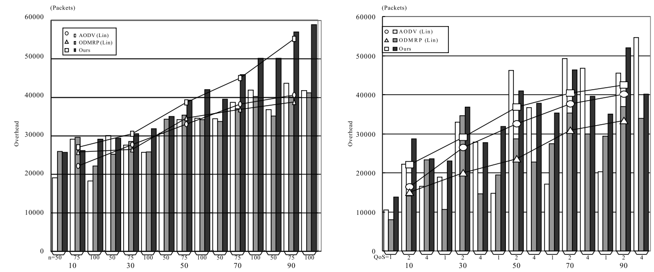
The simulation is run in a $1000 \times 1000\text{-m}^2$ area. The data rate is 2 Mb/s. The duration of each time slot of a time frame is assumed to be 5 ms, and the duration of a control time slot is assumed to be 0.1 ms. The source and destination are randomly selected. Once a QoS request is successful, a time slot is reserved for all 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 consist of the following.

- $Success\ Rate$ (SR): The number of successful QoS multicast routes divided by the total number of QoS



(a) (b)

Fig. 11 Performance of success rate (SR) vs. effect of (a) the number of mobile hosts (n), and (b) the size of the bandwidth requirement.



(a) (b)

Fig. 12 Performance of overhead (OH) vs. effect of (a) the number of mobile hosts, and (b) the size of the bandwidth requirement.

multicast requests, which are initiated from a source to all destination hosts.

- *Overhead* (*OH*): The total numbers of transmitted packets, including the control packets.
- *Throughput* (TP): The number of received data packets for all destination hosts divided by the total number of data packets sent from the source host.
- *Average Latency* (*AL*): The interval from the time the multicast is initiated to the time the last host finishes its multicasting.

It is worth mentioning that an efficient QoS multicast protocol is achieved by having a high SR and TP, and a low *OH* and *AL*. In the following, we illustrate our simulation results of SR, *OH*, TP, and *AL* from various perspectives.

4.1 Performance of Success Rate vs. Mobility

The simulation results of AODV(Lin), ODMRP(Lin), and LTM protocols are shown in Fig. 11 to reflect the performance of SR vs. mobility. The average SR is obtained by calculating the average value of all estimated SR values. Two kinds of effects are discussed.

1A) *Effect of the number of mobile hosts*: Each value in Fig. 11(a) was obtained by assuming that the transmission radius is 100 m, the bandwidth requirement is two time slots, and the number of mobile hosts ranges from 50 to 100 (denoted as n). All protocols has lower *SR* value at the higher mobility as shown in Fig. 11(a). A higher *SR* indicates that a better scheme was achieved. Figure 11(a) shows that the LTM scheme has a higher *SR* than do the other schemes even with various numbers of mobile hosts and values for mobility. For example, the average *SRs* of AODV(Lin), ODMRP(Lin), and LTM are 43%, 58%, and 66%, respectively, when the mobility of hosts was 0–90 km/h. To see the effect of the number of mobile hosts, the greater the number of mobile hosts there is, the higher the *SR* will be. This is because that better *SR* value will be obtained if a MANET with a greater number of mobile hosts.

1B) *Effect of the size of the bandwidth requirement*: Each value in Fig. 11(b) was obtained by assuming the number of mobile hosts to be 75 and the size of the bandwidth requirement to be one, two, and four. Figure 11(b) shows the success rate of searching a QoS multicast route vs. the bandwidth requirement. Observe that our approach has a higher success rate compared to the AODV(Lin) and ODMRP(Lin) schemes under bandwidth requirements are two and four. If the bandwidth requirement is one, our scheme has the similar *SR* value with AODV(Lin) and ODMRP(Lin) schemes. This indicates that our proposed protocol outperforms AODV(Lin) and ODMRP(Lin), especially if the bandwidth requirement is high. This is shows that our lantern-tree scheme can improve the *SR*.

4.2 Performance of Overhead vs. Mobility

The simulation results shown in Fig. 12 illustrate the performance of overhead vs. mobility. The average *OH* was obtained by calculating the average value of all estimated *OH* value. Our approach aims to obtain a more stable QoS routing result, by sacrificing the extra overhead cost. That is, our approach increases the amount of the extra control packets to offer the better results of success rate, throughput, and average latency. Two kinds of effect are described below.

2A) *Effect of the number of mobile hosts*: Each value in Fig. 12(a) was obtained by assuming that the transmission radius is 100 m, the bandwidth requirement is two time slots, and the number of mobile hosts ranges from 50 to 100. A lower *OH* indicates that a scheme is better. Figure 12(a) shows that our scheme has a higher *OH* than do the others. In a MANET, network topologies frequently change when there are more mobile hosts with mobility. Because our protocol collects the network information as usual, the network topology often changing will result in our protocol having a higher overhead.

2B) *Effect of the size of the bandwidth requirement*: Each value in Fig. 12(b) was obtained by assuming that the number of mobile hosts was 75 and the size of the bandwidth requirement was one, two, and four. Figure 12(b) shows the *OH* of searching a QoS route vs. the bandwidth requirement. Observe that our approach acquires a more number of *OH* than does the

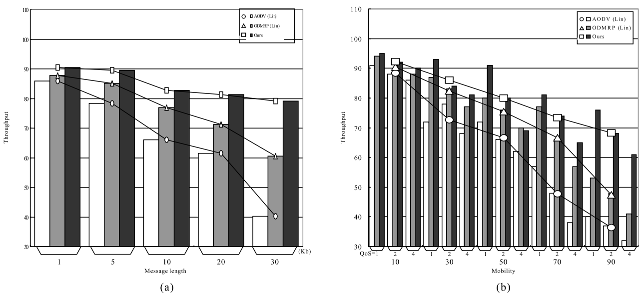


Fig. 13 Performance of throughput (TP) vs. effect of (a) the number of the message length, and (b) the szie of the bandwidth requirement.

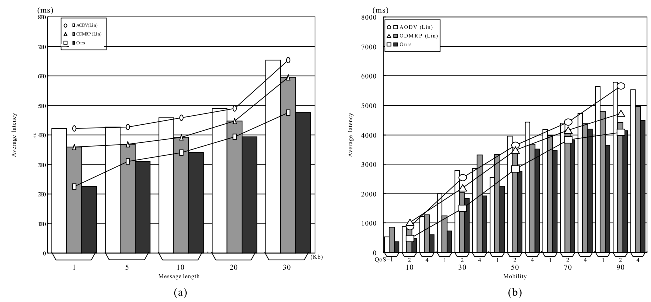


Fig. 14 Performance of average latency (AL) vs. the effect of (a) the size of the message length, and (b) the size of the bandwidth requirement.

AODV(Lin) and ODMRP(Lin) protocols under bandwidth requirements from one to four. Our scheme can indeed control and reduce the time cost because that all possible lanterns are maintained before any QoS requests.

4.3 Performance of Throughput

The simulation results of AODV(Lin), ODMRP(Lin), and LTM protocols are shown in Fig. 13 which reflect the effects of throughput. To examine the performance of TP, two kinds of effects are discussed.

3A) *Effect of the size of the message length*: Each value in Fig. 13(a) was obtained by assuming the transmission radius to be 100 m, the number of mobile hosts to be 75, the bandwidth requirement to be two time slots, while the mobility was 50 and the size of the message length ranged from 1 to 30 Kb. A higher *TP* indicates a better scheme. Figure 13(a) shows that the LTM scheme has a better *TP* than do the other schemes at various message lengths. For example, *TP (throughput)* values of AODV(Lin), ODMRP(Lin), and LTM are 40%, 61%, and 79%, respectively, when the message length is 30 Kb.

3B) *Effect of the size of the bandwidth requirement*: Each value in Fig. 13(b) was obtained by assuming that the number of mobile hosts was 75 and the size of the bandwidth requirement was one, two, and four. Figure 13(b) shows the throughput of searching a QoS multicast route vs. the bandwidth requirement. Observe that our approach has a higher throughput. This indicates that the LTM protocol is better than AODV(Lin) and ODMRP(Lin) protocols, even if the bandwidth requirement is high. This is because our lantern-tree scheme improves *TP (throughput)*. For example, Fig. 13(b) illustrates that if the bandwidth requirement is four and the mobility is 90, our *TP (throughput)* (68%) is higher than AODV(Lin)'s *TP* (36%) and ODMRP(Lin)'s *TP* (47%).

4.4 Performance of Average Latency

The simulation results are illustrated in Fig. 14 and reflect the performance of *AL* vs. load and mobility. Two kinds of effects are discussed below.

4A) *Effect of the size of the message Length*: The simulation assumption is the same as in case *3A*. A lower *AL* indicates a better scheme. Figure 14(a) shows that our scheme has a lower *AL* than do the other schemes. For example, the average *AL* values of AODV(Lin), ODMRP(Lin), and LTM are 6543, 5951, and 4760 ms, respectively, when the message length is 30 Kb. This is because that our protocol has extra backup paths and maintains a better *AL*.

4B) *Effect of the size of the bandwidth requirement*: The simulation assumption is the same as in case *3B*. Figure 14(b) shows *AL* vs. the bandwidth requirement. Observe that our approach obtains a lower *AL* than does AODV(Lin) and ODMRP(Lin), when the bandwidth requirement ranges from 1 to 4. This indicates that our proposed protocol has better average latency than other schemes, even if the bandwidth requirement is high. This is because our lantern-tree scheme actually decreases *AL* from Fig. 14. For instance, Fig. 14(b) illustrates that if the bandwidth requirement is 4 and the mobility is 90, LTM's *AL* (4087 ms) is lower than the AODV(Lin)'s *AL* (5653 ms) and ODMRP(Lin)'s *AL* (4721 ms).

As a summary, it is desirable to have a high SR as well as AL. Generally, the higher the SR is, the lower the AL will be. It is beneficial to using our LTM protocol as demonstrated by the simulation results.

5. Conclusions

This article presents a lantern-based QoS multicast protocol for a wireless ad hoc network, especially when the MAC sub-layer adopts the CDMA-over-TDMA channel model. In addition, our approach is possibly applied to different MAC sub-layers, like the TDMA channel model. Our scheme is a uni-path if the network bandwidth is sufficient, our scheme is a multi-path if the network bandwidth is limited. Our lantern-tree-based scheme greatly improves the success rate by means of multi-path routing. Performance analysis results finally demonstrate the achievements of our proposed protocol.

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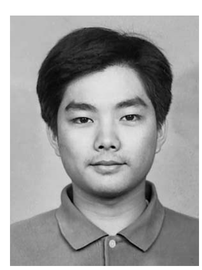

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