A Proactively Maintained Quality of Service Infrastructure for Wireless Mobile Ad Hoc Networks

Moussa Ayyash¹, Donald Ucci² and Khaled Alzoubi³

¹Chicago State University, Technology Education Program, USA  
²Electrical and Computer Engineering Department, Miami University, USA  
³Math and Computer Science Department, Saint Xavier University,  
mayyash@csu.edu, uccidr@muohio.edu, alzoubi@sxu.edu

Abstract: The infrastructureless nature of mobile ad hoc networks poses an extreme challenge for the design of conventional and Quality of Service (QoS) routing protocols. To the best of our knowledge, current QoS routing protocols have primarily been designed to meet QoS metric(s) without concentrating on the robustness of the proposed routing solution. This paper proposes a QoS virtual backbone (QoS-VBB) that can be used for robust QoS routing and monitoring. The proposed QoS-VBB nodes are mainly selected based on individual node stability and available bandwidth for each node. This QoS-VBB has proactive maintenance capability which makes it suitable for dynamic network MANETS' environs. In addition to its preemptive behavior, the proposed QoS-VBB demonstrates several salient features. The analytical studies for the proposed algorithm are presented.

Keywords: Virtual Backbone, QoS, routing, monitoring, Ad Hoc networks, metric.

1. Introduction

Mobile ad hoc networks (MANETs) consist of wireless mobile nodes without reliance on fixed base stations or wired infrastructures. This infrastructureless nature of MANETs poses an extreme challenge for the design of conventional and Quality of Service (QoS) routing protocols.

A simple method of achieving network global broadcasting is by flooding. Unfortunately, blind flooding leads to what is called the broadcast storm problem bringing disastrous consequences and must be avoided in MANETs.

To produce an infrastructure or a virtual backbone (VBB) that is QoS-aware for MANETs' environs, a topology control process is needed [2][5]. This paper proposes a topology control process to construct robust and efficient QoS-VBBS by which QoS routing and network monitoring can be performed. Therefore, the objective is to design QoS-VBBS that last for the MANET lifetime. This is achieved by incorporating a predictive node stability measure $s_n$ and a QoS metric(s) into the selection process of the QoS-VBB nodes. The QoS metric that is considered in this paper is the link bandwidth.

Even though providing a QoS solution for MANETs is complicated, some promising research on QoS routing in MANETs has been conducted. Examples of these algorithms are: Core-Extraction Distribution Ad Hoc Routing (CEDAR) protocol [17], Quality of Service for Ad Hoc Optimized Routing (QOLSR) protocol [4], and Robust Quality of Service Routing (RQoS) protocol [3]. Both CEDAR and QOLSR propose topology control algorithms that extract nodes for network control regardless of their stability conditions or network resources availability. In [3], RQoS defines node stability as a monitor of the variation of the set of neighbors for each node over a predefined period.

The proposed QoS-VBB is of preemptive nature. Existing routing protocols must wait till the computed routes are broken, then they activate their maintenance algorithms. This reactive maintenance capability causes the data packets to be queued and delayed until the route is reestablished. Therefore, reactive maintenance is not suitable for QoS-aware MANETs. Oppositely, our QoS-VBB can be used in devising a preemptive QoS routing algorithm which has a proactive maintenance capability. This maintenance depends on $s_n$, which is a probability function that predicts the next link breakage depending on links lifetime estimation. Then, the QoS-VBB adjusts itself based on the expected lifetime of links. With proactive maintenance, route reestablishment procedures are rarely needed because other routes are discovered prior to current routes breakage. The new QoS-VBB incorporates a stability measure, available bandwidth, and delay metrics in its construction with optimal message and time complexity.

The rest of the paper is organized as follows. In Section 2, the network model and terminology are considered. The derivation of the stability measure is presented in Section 3. Section 4 describes the algorithm. The maintenance aspects are discussed in Section 5. The correctness study is provided in Section 6. Finally, the last section concludes the paper and highlights future directions.

2. Network Model

The network model is represented by an undirected and weighted graph $G(V,E)$, where $V$ represents the graph vertices set and corresponds to network hosts, and $E$ represents the graph edges and corresponds to network links. All nodes in the network have the same maximum transmission range. An edge exists between two vertices iff the distance between them is less than or equal to the maximum transmission range. Such two nodes can communicate with each other directly. This model is known as the Unit Disk Graph (UDG) network model [10]. The weight of the edge represents the available bandwidth of the corresponding link. We make the typical assumption of

¹ Conventional refers to QoS-unaware routing algorithms.
using the well-known IEEE 802.11 standard. Every node $n$ has a unique rank identifier (RID$_n$) and is aware of all nodes that are in its 1-hop vicinity. This 1-hop vicinity awareness is implemented by a local discovery protocol used to construct a 1-hop-neighbors (1hn) table in every node $n$. The discovery process is simply achieved by means of a limited periodic local broadcast of HELLO messages. Each HELLO message carries its source RID field in addition to its STATUS field. This field refers to neighbor's functionality status. A node $n$ can be in one of four states: candidate, dominator, candidate, or pseudodominator. Initially, every node is in candidate status. The structure of the 1hn table that each node carries is clarified in Table I. The $B_a$ column contains the available bandwidth to reach each 1-hop neighbor. The Expiry column represents the lifetime of each table row. The network parameters of any network graph are assumed to be stable during the setup time of any QoS-VBB.

Table I. Structure of 1hn List

<table>
<thead>
<tr>
<th>Node RID</th>
<th>STATUS</th>
<th>$B_a$</th>
<th>Expiry</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Every node $n$ computes a stability measure $s_n$, which reliably represents a predictability measure of node $n$ in conjunction with its links to all 1-hop neighbors. The estimation of $s_n$ is presented in Section III.

3. Stability Measure Estimation

This section concentrates on quantifying individual node stability in MANETs. We refer to the individual node stability by $s_n$ where the subscript $n$ refers to the RID of node $n$.

To date, little work has been done to quantify the individual node stability in MANETs. Instead, poor substitute quantifiers for node mobility have been considered. Examples of these quantifiers are the maximum node speed and pause time [9]. These quantifiers or measures are inadequate since they overlook the fact that MANET nodes are expected to stay in the transmission range of each other. In a dynamic network, a link between any two nodes starts its life once one of these nodes enters the transmission range of the other node and vanishes once any of them leaves the transmission range of the other. In Figure [1], a link $lm$ is formed to join nodes $n$ and $m$ when node $m$ enters the coverage area of node $n$ at point A and exits at point B. The solid and dashed circles represent the transmission ranges, with radius R, of node $n$ and node $m$, respectively.

As shown in Figure [1], node $m$ can reach point B from A using two paths: a straight path and a zigzag path. Obviously, the straight path is unique and the zigzag has infinite possibilities. Each arrow-ended portion of the zigzag path represents an epoch. Hence, the zigzag path in Figure [1] consists of four epochs. In the RWP mobility model, it is most probably for node $m$ to follow the zigzag path during its trip in the coverage area of node $n$. Whenever node $m$ follows the straight path, the lifetime of link $lm$ is the minimum. We refer to the minimum link lifetime by $\tau_{mn}$. The rest of this subsection derives an expression for $\tau_{mn}$, which is then modified to estimate $\tau_p$.

The current literature has several approaches to estimate link lifetime in MANETs [11], [12], [16]. To estimate $\tau_{mn}$, we consider the geometrical approach that is described in [16]. Most importantly, the results in [16] primarily relies on the velocity of the predicting node $n$ without any need to know the relative distances between node $n$ and its direct neighbors. Consequently, it does not assume the availability of link $lm$ during a continuous period, $\tau_p$. Many factors can drastically influence the lifetime of a wireless link. Examples of these factors are signal power, fading, noise, receiver sensitivity, relative velocity (either speed or direction variations), propagation loss, etc. [12]. Each node predicts $\tau_p$ for every link of its 1-hop links. In this section, the procedure of deriving a mathematical expression of $\tau_p$ is presented. This expression predicts how long two nodes are expected to stay in the transmission range of each other.

3.1. $\tau_p$ Estimation

It is useful to remind again that the mutual relationship between any two nodes, $m$ and $n$, is represented in terms of $\tau_{mn}$, which is the probability of the link availability of link $lm$ during a continuous period, $\tau_p$. Many factors can drastically influence the lifetime of a wireless link. Examples of these factors are signal power, fading, noise, receiver sensitivity, relative velocity (either speed or direction variations), propagation loss, etc. [12].

Each node predicts $\tau_p$ for every link of its 1-hop links. In this section, the procedure of deriving a mathematical expression of $\tau_p$ is presented. This expression predicts how long two nodes are expected to stay in the transmission range of each other. In a dynamic network, a link between any two nodes starts its life once one of these nodes enters the transmission range of the other node and vanishes once any of them leaves the transmission range of the other. In Figure [1], a link $lm$ is formed to join nodes $n$ and $m$ when node $m$ enters the coverage area of node $n$ at point A and exits at point B. The solid and dashed circles represent the transmission ranges, with radius R, of node $n$ and node $m$, respectively.
of a Global Positioning System (GPS) to provide spatial information such as relative distances and velocities.

\[ \mathbf{r}_m = (\mathbf{r}_m - \mathbf{r}_n) \]

is follows a uniform distribution in the range [0, 40] m/s.

\[ f_{\mathbf{r}_m}(v, \alpha, \phi) = \frac{1}{(4\pi(b-a))} \cdot \cos(\alpha + \phi) \cdot g(v, \alpha, \phi) \cdot |u(\alpha + \phi)| \]

where \( f_{\mathbf{r}_m}(v, \alpha, \phi) \) is the conditional probability density function of \( \mathbf{r}_m \) given the relative velocity \( v \). The \( f_n \) part is the joint probability density function of \( |\mathbf{r}_m| \) and the phase \( \phi \). The density function \( f_{\mathbf{r}_m}(v, \alpha, \phi) \) can be expressed as follows [15]:

Assuming that \( v \) follows a uniform distribution in a specified range of speeds \([a, b]\) and using Equations 5, 6, 7, 8, and 9, the average expected link lifetime of a link \( l_{nm} \) when node \( n \) travels at \( v \) speed can be computed using the following expression:

\[ \tau_{\mathbf{r}_m} = \frac{\int_0^v f_{\mathbf{r}_m}(v, \alpha, \phi) \, dv}{\int_0^v f_{\mathbf{r}_m}(v, \alpha, \phi) \, dv} \]

where \( \phi_n = \pi - \sin^{-1}(\cos \alpha \gamma_n) \).

Without loss of generality, let \( \alpha = 0 \), then the second term in Equation 10 vanishes. Hence,

\[ \tau_{\mathbf{r}_m} = \frac{A}{2b} \int_{-\infty}^{\infty} \frac{2b \sin \phi_n}{\sin \phi_n} \, d\phi_n \]

Equation 11 can only be numerically integrated to give the \( \tau_{\mathbf{r}_m} \) value. Figure 2 plots \( \tau_{\mathbf{r}_m} \) versus node velocity for \( R = 250 \) meters and \( \gamma_n \) in the range [0, 40] m/s.

Actually, the above results help in finding the average of the expected lifetimes of 1-hop links regardless of how many or how often these links are constructed. For our purposes, we are interested in predicting the lifetime, \( \tau_{\mathbf{r}_m} \), of each 1-hop link \( l_{nm} \). We use \( \tau_{\mathbf{r}_m} \) as a reference value. This reference value is scaled based on the signal strength, \( P_{\text{ref}} \), of the 1-hop neighbor \( m \). The maximum signal strength \( P_{\text{ref}} \) is measured with a very small distance, \( \epsilon \). The minimum signal strength \( P_{\text{min}} \) is measured when node \( m \) is at R distance. To scale \( \tau_{\mathbf{r}_m} \), we divide the transmission range around node \( n \) into five regions: \( R \), \( R \), \( R \), \( R \), and \( R \).

The radius of region \( R \) is \( R/5 \), the radius of region \( R \) is \( 2R/5 \), the radius of region \( R \) is \( 3R/5 \), the radius of region \( R \) is \( 4R/5 \), the radius of region \( R \) is \( R \). These regions are clarified in Figure 3. Once node \( n \) measures \( P_{\text{ref}} \), it estimates the location of node \( m \). Recall that we assume that the epoch length of each node follows an exponential distribution. We further assume that \( \epsilon < R \). After estimating \( x_m \), node \( n \) scales \( \tau_{\mathbf{r}_m} \) using the following equation:

\[ \tau_{\mathbf{r}_m} = \sigma \cdot \tau_{\mathbf{r}_m} \]

where the value of \( \sigma \) is selected as follows: if \( \epsilon < R \), then \( \sigma = \lambda \cdot \epsilon \cdot e^{\lambda R} \), if \( R < \epsilon \leq R \), then \( \sigma = \lambda \cdot \epsilon \cdot e^{\lambda R} \), if \( R < \epsilon \leq R \), then

2 The value of \( \sigma \) is only used as a distinctive parameter and it is not meant to predict exact link lifetime values.

![Figure 1. Active \( l_{nm} \) Link](image)
3.2. Estimation $E_{mn}^{(t_{p})}$

Given the predicted lifetime period $t_{p}$ during which a link $l_{mn}$ stays continuously active, the link availability is defined as [7]:

$$E_{mn}^{(t_{p})} = R_{mn}^{(t_{p})}$$

where $R_{mn}^{(t_{p})}$ is active at time $t_{c} + t_{p}$ (link $l_{mn}$ is active at time $t_{c}$).

The above definition represents a general expression but the detailed expression is as follows:

$$E_{mn}^{(t_{p})} = \frac{\text{e}^{-\lambda t_{p}}}{\lambda}$$

3.3. $s_{n}$ Estimation

Estimating the $E_{mn}^{(t_{p})}$ values for all 1-hop links of node $n$ represents the primary key to estimate its $s_{n}$, which is meant to reflect the stability of a node $n$ in relation to its direct neighbors.

A graph component of size $k$ is defined as a set of $k$ nodes such that $k-1$ of them are connected and rooted to a single node of the component (which is node $n$ in our case). Figure 4 illustrates the concept of a component. To derive a formula for $s_{n}$, we deal with node $n$ as part of a component of size $k$ that, with other components, constructs in the entire $G(V,E)$ graph. Then, $s_{n}$ measures the probability that node $n$ is connected to its component based on the probability link quality $E_{mn}^{(t_{p})}$ values, where $\tau_{mn}$ represents the minimum of all $t_{p}$ values in a component.

In Figure 4, the enclosed component by the dashed border is of size 5. Node $n$ is the node of interest for which we wish to find $s_{n}$. Thus, by computing the probability of having node $n$ as a member of a component of size $k$ as a function of $E_{mn}^{(t_{p})}$ value, we can estimate $s_{n}$. To do so, for a given set of $k-1$ components of size $k$ [14]:

1) The MANET graph, restricted to only $k$-nodes, is connected.

2) An edge connects at least one node of the $k$ nodes with any of the remaining $V-k$ nodes of $G(V,E)$.

As it appears from the conditions, for every node $n$ to compute its $s_{n}$, it needs to check its connectivity with its component members, i.e., with $k-1$ nodes. In addition, node $n$ considers the connectivity of all $k-1$ members amongst their components. However, to satisfy this requirement, each node has to broadcast its connectivity characteristics with its component to all its 1-hop neighbors. The internal connectivity within each component assumes link independency between all links in the component.

Based on the above two conditions, which are also independent, $s_{n}$ is computed using:

$$s_{n} = \frac{1}{\tau_{mn}^{k-1}} \left( \prod_{m=1}^{k} E_{mn}^{(t_{p})} \prod_{m=1}^{k} \tau_{mn}^{(t_{p})} \right)$$
4. ALGORITHM DESCRIPTION

The construction of the QoS-VBB is completed in three phases: in the first phase (Maximal Independent Set (MIS) Construction), we construct a MIS by considering node stability (s_o values) as the first selection criterion. By definition, the MIS is a dominating set (DS). A set is dominating if each node is either in the set (referred to as a dominator) or a neighbor to at least one of the nodes in the set (referred to as a dominatee). In the second phase (Extended-DS (EDS) Construction), we extend, when necessary, the MIS to a larger DS (EDS) by adding additional nodes referred to as pseudo-dominators (PDs). In the third phase (Connected Extended Dominating Set (CEDS) Construction), each dominator identifies the best bandwidth path between itself and each dominator within 3 hop distance, where this path is at most 3 hops. Both of the dominators and the nodes on the identified paths (referred to as connectors) form a QoS-CEDS or QoS-VBB. Note that each pair of dominators with two-hop distance requires one connector (C1) to connect them, and each pair of dominators with three-hop distance requires two connectors (C1, C2). Note that we use the term EDS node for either an MIS node or PD node, and the term non-EDS node for a dominatee node. We also use the notation B^2_v to represent the maximum available bandwidth for node x amongst all its direct links.

Also, this described QoS-VBB uses the assumption that each node is responsible for computing its QoS-metrics.

4.1. MIS Construction

In addition to node n stability s_o, the B^2_v values and RID_v are also involved in the MIS construction:

- Each node n broadcasts periodic Hello messages to all its neighbors. Each Hello message mainly consists of three fields: RID_v, s_o value, and the B^2_v value.
- Once node n obtains all Hello messages from all its 1-hop neighbors, it determines the set of neighbors that have a higher rank than its own, if any. We refer to this set as the eligible dominators set of node n, denoted by (D_v^2). Initially, D_v^2 is empty. A node u has a higher rank than node n, and consequently is added to D_v^2 if one of the following cases applies:

  - If s_u > s_v and B^2_u > B^2_v, node u changes to a PD. If multiple nodes have the same maximum B^2_value, node n selects the node with the lowest RID.
  - Whenever a node u receives a DOMINATEE message from node n, it has the following possibilities:
    - If its D_v^2 set has at least one node, it waits until it receives a response from its nominated potential dominator, then:
      - If its potential dominator becomes a dominator, it nomintes the candidate node (if any) with next highest B^2_v in its D_v^2 set, as a potential dominator. If all its potential dominators have become dominatess, it accepts domination of node n and declares itself as a dominator by sending a unicast DOMINATOR message to node n.
      - If it receives a DOMINATOR message from a potential dominator, then node u switches its status to dominante. Therefore, the received DOMINATEE message from node n is implicitly rejected.
    - Once node n receives a DOMINATOR message, it switches its status from candidate to dominatee.
    - Once a candidate node n realizes that all its neighbors have become dominatees, it becomes a dominator.

4.2. EDS Construction

The purpose of this phase is to guarantee that each node is directly connected by its maximum bandwidth edge to the QoS-VBB. If the maximum bandwidth edge of a dominatee is incident at another dominatee, it is enough to switch one of the dominatees to become a PD. Therefore, after the MIS construction. If B^2_v is for a link between dominatee u and dominatee v, where v is a dominatee, and none of the links with any of the dominators in u's vicinity has the same maximum value, u acts as follows:

- If s_u > s_v, node u changes to a PD.
- If s_u = s_v and RID_u < RID_v, node u changes to a PD.
- If both of the above conditions are false, node u sends a PD-REQUEST to node v.
- Whenever node v receives a PD-REQUEST addressed to itself, it switches its status to a PD.

4.3. QoS-CEDS Construction

Any QoS-CEDS of a MANET must guarantee full connectivity of all EDS nodes. Generally, a fully connected graph is a graph in which any node n can find a path to any other graph node throughout the graph links. Consequently, if the EDS nodes are guaranteed to be fully connected, all G(V,E) nodes will be able to reach each other through EDS nodes. As shown in [2], for any two complementary subsets of an EDS, there exists at least one path that connects them with at most three hops. This indicates that every EDS node must have at least one path of 1-, 2-, or 3-hop length to connect to the rest of the EDS. Therefore, prior to building a CEDS that guarantees a MANET full connectivity, an awareness procedure is required in order for every EDS node to become aware of all other EDS nodes that are two or three hops away from the current node.
hops apart and the available bandwidth \( B_D \) to reach them. Two messages are dedicated to accomplish this vital 2- and 3-hop awareness:

a) 1-hop-dominating (1hD) message. Each 1hD message consists of the source's RID, 1-hop neighboring dominators RIDs, and the \( B_D \) values to reach each dominator listed in the message.

b) 2-hop-dominating (2hD) message. Each 2hD message carries the source's RID, the 2-hop neighboring dominators RIDs, and the \( B_D \) values to reach each of these dominators from the transmitter of the 2hD message.

With the help of the 1hD and 2hD messages and its 1h table data structure, each EDS node constructs three more data structures: the 2-hop-dominating (2hD) list, the 3-hop-dominating (3hD) list, and the 123-hop-dominating (123hD) table. Each EDS node is already aware of all 1-hop DS neighbors by the HELLO messages. After the completion of the EDS, the following steps commence:

- Each dominatee node \( d \) broadcasts a 1hD message.
- Whenever a dominator node \( D \), receives a 1hD message from \( d \), it adds the RID of each dominator into its 2hD list. To ensure the best bandwidth path to these dominators, \( D \) compares the bandwidth \( B_D \) of its link to \( d \) with the bandwidth value for each dominator in the received 1hD message. For each dominator in the 1hD message, if \( B_D \) is less than the bandwidth value of the dominator, \( D \) replaces the bandwidth value for that dominator with \( B_D \). Notice the same dominator may be reported by different dominatees, and thus may appear in the list more than once. Dominators are sorted in the 2hD list in a lexicographical order of the bandwidth.
- Whenever a dominatee node \( d \) receives a 1hD message, it waits until it receives 1hD messages from all its dominatee neighbors. Then, it sends a 2hD message to all dominators in its vicinity. The bandwidth value for each dominator in the 2hD message is determined by the bandwidth value of the dominator in the received 1hD message and the bandwidth value of the link that carried the 1hD message, referred to as \( B_{2d} \). For each dominator in the 2hD message, if \( B_{2d} \) is less than the bandwidth value of the dominator, \( D \) replaces the bandwidth value for that dominator with \( B_{2d} \); otherwise, the bandwidth stays the same.
- Whenever a dominator node \( D \) receives a 2hD message from a dominatee node \( d \), it adds the RIDs of each dominator into its 3hD list. To ensure the best bandwidth path to these dominators, \( D \) compares the bandwidth \( B_D \) of its link to \( d \) with the bandwidth value for each dominator in the received 2hD message. For each dominator in the 2hD message, if \( B_{2d} \) is less than the bandwidth value of the dominator, \( D \) replaces the bandwidth value for that dominator with \( B_{2d} \). Notice the same dominator may be reported by different dominatees, and thus may appear in the 3hD list more than once; it is also possible that the same dominator exist and this is practical for backup paths. Dominators are sorted in the 3hD list in a lexicographical order of the bandwidth.
- After a dominator node \( D \) receives all 1hD and 2hD messages from all dominatees in its vicinity, it identifies the best paths to all dominators within 3-hop distance. To maintain these paths, \( D \) builds its 123hD table. Table 2 shows an example on the structure of a 123hD table. This table retains the following information: (1) The RIDs of all 1-, 2-, and 3-hop surrounding dominators. (2) The number-of-hops required to reach each of these dominators. (3) The RIDs of the dominatee nodes (connectors) on the paths to dominators within a 3-hop distance. If no connectors are required, the entry pair will be (NULL, NULL). If only one connector is required, the pair will be \( (RID_{D1}, \text{NULL}) \). If two connectors are needed, the pair takes the form \( (RID_{D1}, RID_{D2}) \). (4) The available bandwidth \( B_D \) of the necessary links to reach these dominators. Only the \( \text{best} \) \( B_D \) values are only stored, i.e. the 123hD table does not store all possible 1-, 2-, and 3-hop paths. (5) The Expiry time of each table row.

### Table II. Structure of the 123hD Table

<table>
<thead>
<tr>
<th>Dominator RID</th>
<th>Number of Hops</th>
<th>Connectors Pair (C1, C2)</th>
<th>Ba</th>
<th>Expiry</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5. QoS-VBB MAINTENANCE

Providing a consistent quality of service performance in environments with dynamic nature, such as in MANETs, is a key robustness feature of any proposed QoS infrastructure. Varying mobile network dynamics can be due to many reasons. In MANETs, node mobility is a common source of network dynamics. Maintenance is responsible for keeping the QoS-VBBs continuously connected while node mobility is low or moderate. That is, if the QoS-VBB is disconnected in any of its parts, it must be repaired and fixed in order to resume the VBB connectivity. Due to the distributed fully localized and self-healing nature of the design of our QoS-VBB, the maintenance process is interestingly simple; however, this simplicity does not sacrifice the algorithmic efficiency.

Maintenance requires that the EDS and its properties to be kept intact. The proposed QoS-VBB is preemptive due to the fact that it is constructed using a predictive stability measure. This measure allows every node to predict the status of its relationship with its graphic component. Therefore, it proactively re-computes its stability measure prior to the expiration of its graphic component lifetime. Then, it adjusts its status, when necessary, to reflect the new stability conditions. Dominators simply update their tables and lists accordingly. This proactive maintenance provides a vehicle
by which a MANET is continuously served by a preemptive QoS-VBB.

6. QoS-VBB Correctness Analysis

This section presents several lemmas and theorems by which the features of the proposed QoS-VBB are revealed.

**Lemma 1:** The set of dominators generated by our QoS-VBB forms a DS and the MIS has a constant approximation ratio of 5.

The proof of the above lemma is provided in [2].

**Theorem 1:** Let \( m \) be the number of nodes in the graph \( G(V,E) \). Then, both of the time complexity and the message complexity of the proposed MIS for \( G \) is \( O(m) \).

**Proof:** It is obvious from the construction process that each node sends a constant number of messages. Thus the total number of messages is \( cm \), where \( c \) is a constant and \( m \) is the total number of nodes. Thus, the message complexity is \( O(m) \). To calculate the time complexity, we consider the worst case scenario that occurs when all the nodes are ordered in ascending or descending order of their rank. In this case, whenever a node sends a DOMINATEE message, it must wait for all nodes with lower rank. The node with the lowest rank will have to wait the most, since it must wait for all \( m-1 \) nodes that have a higher rank. Thus, the time complexity is \( O(m) \).

Note that the only messages that may be incurred during the EDS construction are the PD-REQUEST messages. Thus, the message complexity is still \( O(m) \). The only time complexity of this procedure is the processing time, where each dominatee node needs to calculate its maximum bandwidth edge, and compares it to the maximum bandwidth edge that is incident at one of the dominators in its vicinity.

**Lemma 2:** The time complexity and the message complexity for completing the QoS-VBB is \( O(m) \), where \( m=|V| \).

**Proof:** We showed that the construction of the MIS and the extended DS requires \( O(m) \) messages in \( O(m) \) time. The CEDS construction phase requires a constant number of messages from each node. The total number of messages for this phase is \( O(m) \) and, hence, the total number of messages for constructing the QoS-VBB is \( O(m) \). In the CEDS construction phase, each dominatee node needs to wait for \( 3hD \) messages from its neighboring dominatees before it sends the \( 2hD \) message, this can be done in \( O(m) \) time, and each dominatee node needs to wait for \( 2hD \) messages from its neighboring dominatees before it builds its \( 12hD \) table. Thus, the total time complexity is \( O(m) \).

**Definition 1:** The maximum bandwidth path between any two nodes as the path that offers the maximum bandwidth, which is measured by the bottleneck edge on the path. To obtain the maximum bandwidth path, we need to maximize the bottleneck edge of any path.

**Definition 2:** The best path between any two nodes in a graph \( G \) is the path that offers the maximum bandwidth with the least possible number of hops.

**Theorem 2:** For any given MANET graph \( G(V,E) \), the maximum bandwidth path (the bottleneck bandwidth) between any two nodes from \( V \) can be provided over our QoS-CEDS.

**Proof:** Let \( u \) be the source node, and let \( v \) be the destination node. Let the maximum bandwidth path follow the following nodes in the same order they are listed here: \( ud \ldots d_{i}d_{j}d_{k}v \). Let us assume both the source and the destination are dominators, and assume \( i \leq 2 \). Thus, there are at most two intermediate nodes between the source and the destination; however, by construction of the CEDS, our algorithm selects the connectors that provide the maximum bandwidth. Hence, the intermediate nodes must be connector nodes, and the path from \( u \) to \( v \) must be a path over the QoS-VBB. This also implies: if \( i>3 \) and no more than two consecutive intermediate nodes are dominatees, then the path must be a path over the QoS-VBB. The other cases are proven by contradiction; let us assume that \( i>3 \), and the path consists of more than two consecutive intermediate dominatee nodes (at least two consecutive independent edges); consider three consecutive intermediate nodes with two consecutive independent edges \( d_{i-1},d_{i} \) and \( d_{i},d_{i+1} \), such that \( j<i \). Let \( d_{j} \) be the dominator of \( d_{i-1},d_{i} \) and let \( d_{i} \) be the dominator of \( d_{i},d_{i+1} \). Since the edge \( d_{i},d_{i+1} \) is on the path, this implies the maximum bandwidth path within a 3-hop distance between \( d_{j} \) and \( d_{i+1} \) is smaller than the bandwidth of the edge \( d_{j},d_{i+1} \), and there is no dominator in the vicinity of \( d_{j} \) that has a path of at most 3 hops to the dominator of \( d_{i},d_{i+1} \), where the bandwidth of this path is greater than or equal to the bandwidth of \( d_{j},d_{i+1} \). However, in order for the maximum bandwidth path within a 3-hop distance between \( d_{j} \) and \( d_{i+1} \) to be smaller than the bandwidth of the edge \( d_{j},d_{i+1} \), at least one of the edges \( d_{j},d_{i} \) and \( d_{i},d_{i+1} \) must be smaller than the edge \( d_{j},d_{i+1} \), otherwise the intermediate edge \( d_{i},d_{i+1} \) can be replaced by a path of at most 3 hops from \( d_{j} \) to \( d_{i+1} \). But, by construction of the extended DS, whenever a non-dominator node has an edge incident at another non-dominator node with a bandwidth greater than the maximum bandwidth that connects it to the QoS-VBB, then at least one of the nodes must be a PD. This implies at least one of the nodes \( d_{j} \) or \( d_{i} \) must be a PD. Similarly, if the edge \( d_{i-2},d_{i-1} \) has a higher bandwidth than at least one of the edges \( d_{i-2},d_{i-1} \) and \( d_{i-1},d_{i} \), then at least one of the nodes \( d_{i-2} \) or \( d_{i-1} \) must be a PD. This contradicts our assumption of having two or more consecutive independent edges on a maximum bandwidth path.

**Theorem 3:** Let \( u,v \in V \) be any pair of non-adjacent nodes in \( G \). Let \( G' \) represent the QoS-VBB for the graph \( G \). Let \( h_{G'}(u,v) \) be the minimum-hop maximum-bandwidth path from the source \( u \) to the destination \( v \) over the graph \( G' \), and let \( h_{G}(u,v) \) be the minimum-hop maximum-bandwidth path from \( u \) to \( v \) over \( G' \). Then, \( h_{G}(u,v) \leq 3h_{G'}(u,v)+2 \).

**Proof:** We follow, and modify the proof from [1] to address the bandwidth issue. Let \( u = u_{1},u_{2},...,u_{k} = v \) be a minimum-hop path in \( G \) between \( u \) and \( v \), where \( k = h_{G}(u,v) \geq 2 \). For any \( 0 \leq i \leq k \), let \( u_{i} \) be \( u_{i} \) itself if \( u_{i} \) is in DS; otherwise, let \( u_{i} \) be any node in the DS that is a neighbor of \( u_{i} \) in \( G \). In Theorem 2, we showed that the bandwidth of any edge incident at the two dominatees \( u_{i} \), \( u_{i} \leq 3 \) the maximum bandwidth on the path from \( u_{i} \) to \( u_{i} \), when this bandwidth is available at most at 3 hops. For any \( 0 \leq i \leq k \), \( h_{G'}(u_{i},u_{i+1}) \geq 3 \). From the selection of the CDS, we have \( h_{G}(u_{i},u_{i+1}) = h_{G}(u_{i},u_{i+1}) \). Therefore, \( h_{G}(u_{i},u_{i+1}) \leq 3. \) This implies that \( h_{G}(u_{i},u_{i+1}) \leq 3k \). Thus, \( h_{G}(u,v) = h_{G}(u,v) \leq 3k. \)
This completes the proof.

7. CONCLUSIONS

This paper presented a robust QoS-VBB algorithm that combated MANET dynamics. The new QoS-VBB utilizes our preemptive stability measure. Salient features of this QoS-VBB are discussed in this paper. The key feature is the incorporation of a stability measure, available bandwidth, and delay metrics in the QoS-VBB construction. The maintenance issue is easily addressed by the algorithm's normal operation. The analytical results reveal attractive features. Our QoS-VBB has the following advantages: 1- It is fully localized (no spanning tree is needed and VBB maintenance is simple and done locally); 2- The nodes that are in charge of routing are the most stable nodes in their domains; 3- The maximum bandwidth path between any two nodes in the graph runs over the QoS-VBB; 4- The number of hops of the best path over the QoS-VBB is at most 3 times the number of hops of the best path; 5- The number of nodes in the MIS are relatively small (within 5 of the minimum MIS); 6- Both of the message complexity and time complexity are \( O(m) \), where \( m = |V| \). Our future work includes an extension of the proposed QoS-VBB to deal with effective topology construction and routing.

REFERENCES


