International Journal on Electrical Engineering and Informatics - Volume 4, Number 2, July 2012

A Framework for a Minkowski Distance Based Multi Metric Quality of Service Monitoring Infrastructure for Mobile Ad Hoc Networks

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Abstract: As a result of the rising popularity and necessity of real-time multimedia applications, Quality of Service (QoS)monitoring needs more attention in wireless networks. Due to infrastructureless and mobile nature of wireless mobilead hoc networks (MANETs), QoS monitoring is a challenging task. This paper extends our previously published workand provides a framework for a robust and a multi-metric QoS monitoring infrastructure (MMQoSMI) for MANETs.Three QoS metrics (delay, jitter, and packet loss) are considered by the proposed QoS monitoring framework. TheMMQoSMI nodes are mainly selected based on individual node stability and available bandwidth for each node.Then, these nodes are implicitly connected using link bandwidth and delay as QoS metrics. For an MMQoSMInode to measure the QoS metrics of its directly connected links, it relies on the Minkowski distance approach.This approach measures the selected QoS metrics and then enters them to the distance assessment system whileconsidering customer's QoS requirements of each multimedia application. As a result, MMQoSMI nodes combinethe selected QoS metrics and produce an output that represents the instantaneous QoS. Every node in the MANETassesses the available QoS and then forwards it to its cluster-head node to be used for network monitoring and otherpurposes.

Index Terms: Ad Hoc Networks, Quality of Service, Virtual Backbone, Minkowski Distance, Monitoring, Euclidean Distance,Node Stability

I. Introduction and Related Work

Different applications have different *Quality of Service* (QoS) requirements that need to be carefully met in orderto fulfill customer's needs [1]. The evolution of wireless mobile networks and real time applications introduces newchallenges in supporting predictable and reliable communication performance. These challenges are a consequenceof the vastly increasing number of current and future multimedia products that find application not only in fixedwireless networks but also in the mobile environment [2].

Wireless *mobile ad hoc networks* (MANETs) have become a rapidly growing field. Applications of MANETsoccur in situations such as emergency search-and-rescue operations, meetings or conventions in which users wish toquickly share information, and data acquisition operations in hostile terrain. In situations like battlefields or majordisaster areas, ad hoc networks need to be deployed immediately without base stations or wired infrastructures.These networks are typically characterized by scarce resources (bandwidth, power, etc.), lack of established backboneinfrastructure, high error rates, and a dynamic topology [3].

QoS can be estimated and specified in terms of several *metrics* that are of prime importance to the applicationunder consideration. Typical QoS metrics are available bandwidth, delay, jitter, tolerable packet loss rate and/ornumber of hops, and path reliability [4]. While gaining more interest, QoS support is yet to become a commonreality and is still an open research territory especially for multimedia applications.

One of the practices that leads to performance degradation in networking, in general, is the practice of broadcastinginformation globally throughout the network. A simple method of

Received: October 10th, 2011. Accepted: June 20th, 2012

achieving global broadcasting in MANETs is by*flooding*. Unfortunately, blind flooding leads to serious problems such as heavy contention, intense collisions, and redundant rebroadcasts. Such practices cause the so-called *broadcast storm problem* bringing disastrous consequencesand must be avoided in MANETs [5].

Generally, the QoS problem is intricate [6]. When it comes to MANETs, the problem becomes more complicated[4]. The added complexity follows logically because of the special characteristics of the MANET networkingplatform and the continuous monitoring of the QoS metrics.

Even though the QoS problem suffers from these obstacles, some promising research on QoS routing in MANETshas been done. Examples of these algorithms are: Core-Extraction Distribution Ad Hoc Routing (CEDAR) [7],Quality of Service for Ad Hoc Optimized Routing Protocol (QOLSR) [8], and Robust Quality of Service RoutingAlgorithm for Wireless Mobile Ad Hoc Networks (RQoSR) [9]. Both CEDAR and QOLSR select nodes for networkcontrol regardless of their stability conditions; however, RQoSR considers node stability in selecting MANET'svirtual infrastructure.

Network monitoring is necessary for effective network management. Therefore, network managers pay closeattention to network monitoring techniques, algorithms, and tools. Network monitoring systems are important foroptimizing the usage of network resources which are used for functions such routing, load balancing, traffic analysisand engineering [10].

This work is to propose a *multi-metric QoS monitoring infrastructure (MMQoSMI) for MANETs*. This infrastructure relies on decreasing the number of nodes that participate in the monitoring process. Therefore, we study theimpact of overlaying a *virtual backbone* (VBB) on MANETs and performing traffic monitoring process via thisVBB. The VBB should have a minimal number of nodes and should support an efficient and robust means ofinformation collection from all nodes in the VBB. In other words, MMQoSMI searches for a set of nodes whichin turn will form the VBB and, most interestingly, this VBB will serve as the infrastructure backbone of thenetwork even though MANETs are infrastructureless networks. Once the VBB is established, its nodes will assessits available QoS resources. A QoS assessment system was proposed in [11]. This assessment system relies onthe quantified distance evaluation between two vectors. This approach is based on the concept of Euclidean and Minkowski distance measures [12]. Minkowski distance is a formula derived from Pythagoras metric. It is thedistance between two vectors which may be defined as the geometric distance between two inputs with a variablescaling factor, power ( ). This distance is the generalised distance as can be seen in Equation 1 [13]:

$$d_{ij} = \sqrt{\sum_{k=1}^{n} (\chi_{ik} - \chi_{jk})\gamma} \qquad (1)$$

When γ is *one*, the Minkowski distance is equal to the *Manhattan* distance. When it is *two* it yields the Euclidiandistance between two vectors.

In this paper, the distance measure approach is used to combine three QoS metrics: delay, jitter, and packet loss.The output of this system represents the QoS level provided to the application based upon the network conditionscompared to the QoS level needed for that application.

The justification for using the distance approach can be found in [11]. Luckly, the distance approach is uncomplicated and mathematically straightforward; it relies on one equation and a simple mapping process.

The proposed framework consists of two phases: *Phase I:* The formation of a QoS infrastructure, or a *virtualbackbone* (VBB). This infrastructure is a bandwidth-based and stability-aware *QoS virtual backbone* (QoS-VBB)and it will be used for QoS monitoring [14]. One of the novelty features of the proposed QoS-VBB is its *preemptive*nature. Successful

QoS-VBBs need to posses the following features: robustness, efficiency of construction, ease ofmaintenance, and competitive performance measures. *Phase II:* The assessment and monitoring of QoS metrics. Insummary, the proposed MMQoSMI will be the core of network resources monitoring.

The literature shows several protocols for QoS monitoring and network management over conventional networks.One of the protocols for the management of ad hoc networks is the *Ad hoc Network Management Protocol*(ANMP) [15]. This SNMP-compatible management architecture is based on node clustering using specific clusteringalgorithms. Then a three-level hierarchy (manager, cluster-heads, and simple nodes) is constructed. The simple nodescollect the information locally and then send it to the cluster head. The cluster heads filter the required informationand submit them to the overall manager.

The GUERILLA framework is a self-management approach for ad hoc networks. This was proposed to solve theproblem of unpredictable behaviour of the MANETs [16]. In [17], an *Intrusion Detection System* for ad hoc networkshas been proposed to monitor and detect network attacks and misbehaviour performances based on distributedschemes of network monitoring. In [18], a resource monitoring architecture for MANETs is presented. Preliminary experience indicated that the monitoring system is agile enough to run in a highly MANET. A monitoring algorithmin OLSR-based ad hoc networks was presented in [19]. This was proposed to collect parameters from nodes withoutconsuming network resources. It was shown that this approach reduces problems associated with monitoring anddata collection in wireless networks compared with other monitoring approaches.

The rest of the paper is organized as follows. In Section II, the terminology and assumptions are considered.The estimation of node stability measure is shown in Section III. Section IV describes Phase I of MMQoSMI, andthe maintenance aspects. In Section V, Phase II of MMQoSMI is presented. Finally, the last section concludes thepaper and highlights future directions.

2. Terminology and Assumptions

Devising MMQoSMI relies on the following assumptions:

1) Every node *n,* which has a unique *rank-identifier* RID, knows all nodes that are in its 1-hop vicinity. This 1-hop vicinity *awareness* can be implemented by a *local discovery protocol* used to construct a *1-hop-neighbors*(1hn) table for every node n. The discovery process is simply achieved by means of a limited periodic localbroadcast of *HELLO* messages. Each *HELLO* message, which represents the core of the discovery protocol,carries its source RID field in addition to its STATUS field. The STATUS field refers to the node's functionalitystatus. A node n can be in one of four states: *candidate, dominatee, dominator, or pseudo-dominator*. Initially,every node is in candidate status. The STATUS field is continuously updated depending on the changes ofthe status of the source of the *HELLO* message. The structure of the *1hn* table that each node carries isclarified in Table I. The BW column contains the bandwidth values available to reach each 1-hop neighbor.The Expiry column represents the lifetime of each row of the *1hn* list.
2) A MANET is modeled as a *Unit Disk Graph* (UDG) [20].
3) Every node *n* computes a stability measure sn as shown in Section III. sn represents a a *predictability measure*of node *n* in conjunction with its links to all 1-hop neighbors.

Table 1. Structure of 1hn list

Node RID	STATUS	BW	Expiry
. . .			
n			
. . .			

3. Stability Measure Estimation

This section concentrates on the quantification of individual node stability in MANETs. We refer to the individualnode stability by *s*n where the subscript *n* refers to the RID of the node. The purpose is to select the most stablenodes amongst their neighbors to be part of the QoS-VBB.The measure, *s*n, is a stability measure that reliably represents node *n* as an interactive measure of node *n* inconjunction with its links to all 1-hop neighbors. Consequently, *s*n is a measure that is based on the future predictionof all direct 1-hop links behavior. Thus, it is a measure that relies on the prediction information of links availabilityrather than their history. This predictive approach is suitable for wireless MANETs that exhibit great degree ofvariability due largely to mobility.

For each link *i* of node *n*, link availability is represented by $L_n^i(\tau_p)$, where τ_p is the predicted lifetime periodof link *i*. $L_n^i(\tau_p)$ is defined as the probability of link availability of link *i* during the τ_p period. The τ_p period ispredicted prior to estimating $L_n^i(\tau_p)$. Each node *n* is responsible to compute its $L_n^i(\tau_p)$ values for all its 1-hop direct links. Then, s_n is computed. There are many factors that affect link availability such as propagation loss, multipath interference, direction, and speed of motion, etc. [21]. Each s_n depicts a *predictability measure* of the stability of node *n* is in terms of its 1-hop relationships. The remaining part of this section presents the mathematical relationson methods to compute $L_n^i(\tau_p)$ and subsequently s_n. The derivation process of *s*n is summarized as follows:

(1) Derive an expression for computing τ_p of each 1-hop link. (2)Present and discuss the mathematical resultsused to compute $L_n^i(\tau_p)$ [22]. (3)Derive the mathematical expression for s_n. The main assumptions utilized during the derivation process of s_n are very similar to those used in the literaturesuch as [22][23][24] and they are:

1) Individual node mobility is uncorrelated and links fail independently.
2) Based on the random nature of MANETs, each node *n* follows a sequence of random length intervals called*mobility epochs* during which the direction and speed stay constant. The direction and speed of each nodechanges randomly from epoch to epoch. Mobility epoch lengths follow an exponential distribution with mean λ^{-1}, such that,

$$P\{epoch \le \chi\} = 1 - e^{-\lambda\chi} \tag{2}$$

   Each node has the same epoch length λ^{-1} mean.
3) The direction of each mobile node throughout each epoch is *independent and identically distributed* (i.i.d.)with a uniform distribution over [0, 2 π] [25].
4) Each node has *bidirectional* communication links with its neighbors within the UDG.
5) The node's speed, direction, and location are mutually independent.

A. τ_p Estimation

It is useful to remind again that the mutual relationship between any two nodes, *m* and *n*, is represented in termof $L_n^i(\tau_p)$, which is the probability of the link *availability* of link l_{mn} during a continuous period, τ_p. Many factorscan 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), etc. [25].

Each node must be able to predict τ_p for every link of its 1-hop links. In this section, the procedure of derivinga mathematical expression of τ_p is presented. This expression predicts how long two nodes are expected to stay inthe transmission range of each other. In a dynamic network, a link between any two nodes starts its life once one ofthese nodes enters the transmission range of the other node and vanishes once any of them leaves the transmissionrange of the other. In Figure 1, a link l_{mn} is formed to join nodes *n* and *m* when node *m* enters the coverage areaof node *n* at point A and exits at point B. The solid and dashed circles represent the transmission ranges, withradius 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 thezigzag path represents an *epoch*. Hence, the example we show in Figure 1 consists of *four* epochs. In the *random-waypoint* (RWP) mobility model, it is most probably for node *m* to follow the zigzag path during its trip in thecoverage area of node *n*. Whenever node *m* follows the straight path, the lifetime of link l_{mn} is the *minimum*. Werefer to the minimum link lifetime by $\tau_p^{\min}$. The rest of this subsection derives an expression for $\tau_p^{\min}$, hich isthen modified to estimate τ_p .

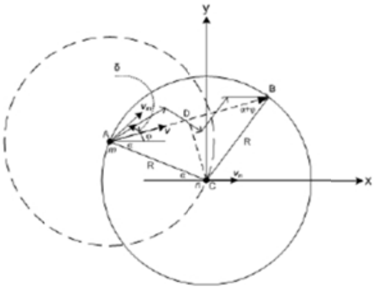


Figure 1. Active l_{mn} Link

The current literature has several approaches to estimate link lifetime in MANETs [24][25][26]. To estimate $\tau_p^{\min}$, we consider the *geometrical* approach that is described in [26]. Most importantly, the results in [26] primarilyrelies 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 a *Global Positioning System* (GPS) toprovide spatial information such as relative distances and velocities.

Again, consider Figure 1. The velocities of nodes *n* and *m* are $\vec{v}_n$ and $\vec{v}m$, respectively. The relative velocity ofnode m with respect to node n is denoted by $\vec{v}$. Using the Cartesian coordinate system and the orthogonal unitvectors $\hat{i}$ and $\hat{j}$, let:

$$\vec{v}_n = |\vec{v}_n| \,.\, \hat{i},$$
$$\vec{v}_m = (|\vec{v}m| \,.\, \cos\delta)\hat{i} + (|\vec{v}m|.\sin\delta)\hat{j}$$

Then,

$$\begin{aligned} \vec{v} &\triangleq \vec{v}_{mn} \qquad (3) \\ &= \vec{v}_m - \vec{v}_n \\ &= (|\vec{v}m| \,.\, \cos\delta - |\vec{v}n|)\hat{i} + (|\vec{v}m|.\sin\delta)\hat{j}. \end{aligned}$$

Using the cosine law, the magnitude of $\vec{v}$ is given by:

$$v = |\vec{v}|$$

$$= \sqrt{|\vec{v}_n|^2 + |\vec{v}_m|^2 - 2\,.\,|\vec{v}_n|\,.\,|\vec{v}_m|\,.\,\cos\delta.} \tag{4}$$

and the motion direction of $\vec{v}$ is:

$$\varphi = \tan^{-1}\left(\frac{\sin\delta}{\cos\delta - |\vec{v}_n|/|\vec{v}_m|}\right).$$

The coordinates of point A are (-R . cos α, R.sin α). Since the triangle ΔABC is an isosceles triangle with $\angle CAB = \angle CBA = \alpha + \varphi$. Therefore, the coordinates of point B are (R . cos(α+ φ), R . sin(α + φ)) and the distance $|AD| = R.\cos(\alpha + \varphi)$. Consequently, the distance that node *m* travels within the transmission range of node *n* is $|AB| = 2R\,.\,|\cos(\alpha + \varphi)|$. Hence,

$$\begin{aligned} \tau_p^{\min} &= \frac{|AB|}{|\vec{v}|} \\ &= \frac{2R.|\cos(\alpha + \varphi|}{v} \\ &= \frac{2R.|\cos(\alpha + \varphi)|}{\sqrt{|\vec{v}_n|^2 + |\vec{v}_m|^2 - 2.|\vec{v}_n|\,.\,|\vec{v}_m|.\cos\delta}} \end{aligned} \tag{5}$$

As shown in Equation 5, $\tau_p^{\min}$ is a function of three random variables: α, φ and v. The estimated $\tau_p^{\min}$ value can be used in estimating the *mean* link lifetime, $\overline{\tau_p^{\min}}$, of node *n* as a function of its velocity, $v_n = |\vec{v}_n|\,.\,i.e.\,\overline{\tau_p^{\min}(v_n)}$.

The calculation of $\overline{\tau_p^{\min}(v_n)}$ is performed by computing the expectation of $\tau_p^{\min}$ over α, φ, and v:

$$\overline{\tau_p^{\min}(v_n)} = E_{v\alpha\varphi}\,[\tau_p^{\min}] \tag{6}$$

The right hand side of Equation 6 depends on the joint probability density function of $v, \alpha,$ *and* φ, $f_{v\alpha\varphi}(v,\alpha,\varphi)$ for nodes that enter the transmission range of node *n*:

$$f_{v\alpha\varphi}(v,\alpha,\varphi) = f_{\alpha|\mathrm{v}\varphi}(\alpha \mid v,\varphi).f_{v\varphi}(v,\varphi) \tag{7}$$

where $f_{v|\alpha\varphi}(\alpha \mid \mathrm{v},\varphi)$ is the conditional probability density function of α given the relative velocity $\vec{v}$. The $f_{v\varphi}(v,\varphi)$ part is the joint probability density function of $|\vec{v}|$ and the phase φ. Based on the results presented in the appendix of [27], the density function $f_{v\alpha\varphi}(v,\alpha,\varphi)$ can be expressed as follows:

$$\begin{aligned} f_{v\alpha\varphi}(v,\alpha,\varphi) = &\frac{1}{4\pi.(b-a)} \\ &.v\,.\cos(\alpha + \varphi).g(v,\varphi,v_n) \end{aligned} \tag{8}$$

$$.\{u(\alpha+(\frac{\pi}{2}+\varphi))-u(\alpha-(\frac{\pi}{2}-\varphi))\}$$

where u(.) is the standard unit step function and

$$g(v,\varphi,v_n)=\frac{u(h(v,\varphi,v_n)-a)-u(h(v,\varphi,v_n)-b)}{h(v,\varphi,v_n)} \tag{9}$$

where

$$h(v,\varphi,v_n)=\sqrt{v^2+v_n^2+2vv_n\cos\varphi} \tag{10}$$

Assuming that *v*n follows a uniform distribution in a specified range of speeds [*a*, *b*] and using Equations 6, 7, 8, 9, and 10, the average expected link lifetime of a link *l*mn when node *n* travels at v_n speed can be computed using the following expression:

$$\overline{\tau_p^{\min}(v_n)}=\int_0^{\pi}\int_{-\pi}^{\pi}\int_{-\pi}^{\pi}\tau_p^{\min}.f_{v\alpha\varphi}(v,\alpha,\varphi)=d\alpha d\varphi dv \tag{11}$$

$$=\frac{R}{2(b-a)}(\int_0^{\pi}\log\left|\frac{b+\sqrt{b^2-v_n^2\sin\varphi}}{v_n+v_n\cos\varphi}\right|d\varphi$$

$$-\int_{\varphi 0}^{\pi}\log\left|\frac{a+\sqrt{a^2-v_n^2\sin^2\varphi}}{a-\sqrt{a^2-v_n^2\sin^2\varphi}}\right|d\varphi), \tag{12}$$

where

$$\varphi_o=\pi-\sin^{-1}(a/v_n)$$

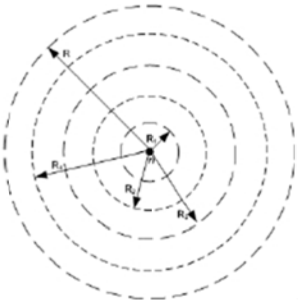
Without loss of generality, let a = 0, then the second term in Equation 11 vanishes. Hence,

$$\overline{\tau_p^{\min}(v_n)}=\frac{R}{2b}\int_0^{\pi}\log\left|\frac{b+\sqrt{b^2-v_n^2\sin^2\varphi}}{v_n+v_n\cos\varphi}\right|d\varphi \tag{13}$$

Equation 13 can only be numerically integrated to give the expected $\overline{T}_p$ value.

An interesting observation of Equation 13 is that as long as the transmission range of a node and its velocity are known, the node can compute the average expected lifetime of its links with its neighbors.

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, τ_p^{mn} of each 1-hop link l_{mn}. To predict the lifetime of a link l_{mn}, we use the results obtained in Equation 13. We use $\overline{\tau_p^{\min}(v_n)}$ as as a *reference value*. This reference value is scaled based on the signal strength, P_m; of the 1-hop neighbor *m*. The maximum signal strength $P_m^{\max}$ is measured with a very small distance, ϵ. The minimum signal strength $P_m^{\min}$ Pmin is measured when node *m* is at *R* distance. To scale $\overline{\tau_p^{\min}(v_n)}$, we divide the transmission region around node *n* into *five* regions: R$_1$, R_2, R_3, R_4, and R_5. The radius of region R_1 is R/5 , the radius of region R_2 is 2R/5, the radius of region R_3 is 3R/5, the radius of region R_4 is 4R/5; the radius of region R_5 is R. These regions are clarified in Figure 2.



p

Figure 2. Regions Around Node *n*

Once node *n* measures P_m, it estimates the location of node *m*, χ_m . Recall that we assume that the epoch length of each node follows an exponential distribution. We further assume that λ < < R. After estimating χ_m , node *n* scales $\overline{\tau_p^{\min}(v_n)}$ using the following equation:

$$\tau_p^{mn} = \sigma .\, \overline{\tau_p^{\min}(v_n)}$$

where and the value of σ is selected as follows:

1) $If\ \varepsilon \le \chi_m \le R_1, then\ \sigma = \lambda\, .\, e^{-\lambda R_1}.$
2) $If\ R_1 < \chi_m \le R_2, then\ \sigma = \lambda\, .\, e^{-\lambda R_2}.$
3) $If\ R_2 < \chi_m \le R_3, then\ \sigma = \lambda\, .\, e^{-\lambda R_3}.$
4) $If\ R_3 < \chi_m \le R_4, then\ \sigma = \lambda\, .\, e^{-\lambda R_4}.$
5) $If\ R_4 < \chi_m \le R_5, then\ \sigma = \lambda\, .\, e^{-\lambda R_5}.$

Hence, for every 1-hop link i :

$$\tau_p^i = \sigma .\, \overline{\tau_p^{\min}(v_n)}$$

$$= \sigma . \frac{R}{2b} \int_0^{\pi} \log \left| \frac{b + \sqrt{b^2 - v_n^2 \sin^2 \varphi}}{v_n + v_n \cos \varphi} \right| d\varphi$$

B. $L_n^i(\tau_p)$ *Estimation*

The important link availability measure $L_n^i(\tau_p)$ which is used in estimating our s_n is discussed in this subsection. Mainly, we adopt the derived expression for $L_n^i(\tau_p)$ that is in [22].

Given the predicted lifetime period τ_p^i during which a link l_{mn} stays continuously active, the link availability is defined as:

$$L_n^i(\tau_p) \underset{=}{\Delta} \ \mathrm{P_r}\{\text{link } l_{mn} \text{ is active at time } t_0 + \tau_p$$

$$\mid \text{link } l_{mn} \text{ is active at time } t_0\}$$

The above definition represents a general expression but the detailed expression is as follows [22]:

$$L_n^i(\tau_p^i) = \frac{1-e^{-2\lambda\tau_p^i}}{2\lambda\tau_p^i} + \frac{\lambda\tau_p^i e^{-2\lambda\tau_p^i}}{2} \tag{15}$$

C. s_n Estimation

Estimating the $L_n^i(\tau_p^i)$ values for all 1-hop links of node *n* represents the primary key to estimate its s_n. We need these probability values Lin(p) since sn is meant to reflect the stability of a node *n* in relation to its direct neighbors.

To derive a formula for sn, 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 compone based on the probability link quality $L_n^i(\tau_{\min}^i)$ values, where represents the minimum of all τ_p^i values in a component. A component of size *k* in a graph is defined as a set of *k* nodes such that *k-1* of them are connected

Figure 3. Component Concept for k = 5

and rooted to a single node of the component (which is node *n* in our case). Figure 3 illustrates the concept of a component.

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 $L_n^i(\tau_{\min})$ value, we can estimate sn. To do so, for a given set of *k-1* components of size *k* [28]:

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 sn, 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, sn is computed :

$$s_n = \prod_{i=1}^{k-1} L_n^{(i)}(\tau_{avg_n}) . \prod_{m=1}^{k-1} \prod_{r=1}^{k_m-2} L_m^{(r)}(\tau_{avg_m})) \tag{16}$$

$$= \prod_{i=1}^{k-1} \left(\frac{1-e^{-2\lambda\tau_{avg_n}}}{2\lambda\tau_{avg_n}} + \frac{\lambda\tau_{avg_r} \,.\, e-2\lambda\tau_{avg_n}}{2} \right)$$

$$. \quad = \prod_{m=1}^{k-1} \prod_{r=1}^{k_m-2} \left(\frac{1-e^{-2\lambda\tau_{avg_m}}}{2\lambda\tau_{avg_m}} + \frac{\lambda\tau_{avg_r} \,.\, e^{-2\lambda\tau_{avg_m}}}{2} \right)),$$

where k_m represents the size of node *m* component and τ_{avg_m} represents the average predired lifetim of node m gragh component.

4. Phase I: QoS-VBB Formation

The construction of the QoS-VBB consists of four phases: the MIS construction phase, the *extended dominating set* (EDS) construction phase, the *connected extended dominating set* (CEDS) construction phase, and the QoS-VBB maintenance phase.

A. MIS Construction

The MIS nodes are primarily selected based on the stability conditions of the network nodes. This set of *stability aware* nodes represents the core members of the VBB. Let B_a^n be the maximum available bandwidth for node n amongst all its direct 1-hop links. In addition to node stability, the Ban values and RIDn are also involved in building the MIS set. The construction process of the MIS is as follows:

1) Each node n, which is initially in the *candidate* status, broadcasts periodic HelloDS messages to all its neighbors. Each Hello_{DS} message mainly consists of three fields: n's RID, s_n value, and the B_a^n value.
2) Once node *n* obtains all Hello_{DS} 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_e^n). Initially, D_e^n is empty. A node u has a higher rank of node n, and consequently is added to D_e^n if one of the following cases apply:
    a) $s_u > (s_n + s_{th})$. A stability threshold constant (s_{th}) is used to avoid decisions based on marginal comparisons.
    b) ($s_u \geq (s_n - s_{th})$ and $s_u \leq (s_n + s_{th})$) and $B_a^u > B_a^n$.
    c) ($s_u \geq (s_n - s_{th})$ and $s_u \leq (s_n + s_{th})$) and $B_a^u = B_a^n$ and $\text{RID}_u < \text{RID}_n$.
3) Each node n with a nonempty D_e^n, nominates the candidate node u which has the highest B_a^n in its D_e^n as its dominator. The status of a node in the set D_e^u may change to a dominatee or a dominator. This nomination takes place by sending a DOMINATEE message addressed to node *u*. If multiple nodes have the same maximum B_a^u value, node n selects the node with the lowest RID.
4) Whenever a node *u* receives a DOMINATEE message from node *n*, it has the following possibilities:
    a) If its D_e^u is empty, it accepts the nomination and becomes the *dominator* of node *n* by sending a unicast DOMINATOR message to node *n*.
    b) If its D_e^u set has at least one node, it *waits* until it receives a response from its nominated potential dominator, then:
        i) If its potential dominator becomes a dominatee, it nominates the candidate node (if any) with next highest B_a^u in its D_e^u set, as a potential dominator. The status of a neighbor can be easily detected through the STATUS field in the periodic HELLO messages. If all its

potential dominators have become dominatees, it accepts domination of node *n* and declares itself as a *dominator* by sending a unicast DOMINATOR message to node n.
ii) If it receives a DOMINATOR message from a potential dominator, then node *u* switches its status to dominatee. Therefore, the received DOMINATEE message from node n is implicitly rejected. This rejection is detected by the HELLO messages from node *u*.

5) Once node *n* receives a DOMINATOR message, it switches its status from *candidate* to *dominatee*.
6) Whenever a candidate node *n* realizes that all its neighbors have become dominatees, it declares itself as a *dominator*.

B. Extended-DS Construction

The MIS, which is also a *dominating set* (DS) [29], constructed in the previous section is extended to a larger DS. The purpose of this procedure is to have each node connected directly by its maximum bandwidth edge to the DS. If the maximum bandwidth edge of a dominatee is incident at another dominatee, it is enough to switch one of the dominatees to a *pseudo-dominator* (PD) to ensure the direct connectivity of the edge to the DS. Each dominatee node u determines its maximum available bandwidth B_a^u value. If this value is for a link between u and 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:

- 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.*

The new extended-DS (referred to as EDS) consists of both the MIS nodes and PD nodes. The only messages that may be incurred in this procedure are the *PD-REQUEST* messages. Thus, the message complexity is 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.

The EDS nodes are referred to as *dominators*. Each dominator and all its dominatees are members of what we call a *domain.* Notice that each dominator node also dominates itself.

C. QoS-CEDS Construction

In this section, we use the resulting DS or EDS from Section IV-B to build a QoS-CEDS. Generally, CDSs in the literature are constructed by using the RID of the nodes. Our approach is to develop new types of CDSs that are QoS-aware.

Any *connected dominating set* (CDS) of a MANET must guarantee *full* connectivity of all DS 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 this full connectivity of the DS nodes is guaranteed, all G(V,E) nodes will be able to reach each other through DS nodes. The following lemma describes the connectivity requirement of any DS.

Lemma 1: For any two complementary subsets of a DS, there exists at least one path that connects them with at most three hops [29].

The above lemma indicates that any two subsets of a DS can be connected by *at least* one 1-, 2-, or 3-hop path. Therefore, every DS node must have *at least* one path of 1-, 2-, or 3-hop length to connect to the rest of the DS. Obviously, this path can be comprised of at most two dominatees (i.e. 0,1,2) that can be involved in connecting a DS node to the rest of the DS. Therefore, prior to building a CDS that guarantees a MANET full connectivity, an *awareness* procedure is required in order for every DS node to become aware of all other DS nodes that are two or three hops apart. After each DS node has become aware of the existence of all DS nodes within 3 hops, it searches for the best path to reach them. There are two messages dedicated to accomplish this vital 2- and 3-hop awareness:

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

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

With the help of the *1hD* and *2hD* message and its *1hn* list data structure, each DS node constructs *three* more data structures: the *2-hop-dominators* (2hD) list, the *3-hop-dominators* (3hD) list, and the *123-hop-dominators* (123hD) table. Each DS node is already aware of all 1-hop DS neighbors through 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 (BD) 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 (this is practical for multipath routing [30]). 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*dd. For each dominator in the *2hD* message, if *B*dd is less than the bandwidth value of the dominator, *d* replaces the bandwidth value for that dominator with *B*dd, 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 (BD) 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*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 *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.

Table 2. Structure of The 123hD Table

Dominator RID	Number of Hops	Connectors Pair (C_1 ,C_2)	Ba	Expiry
⋮				
D				
⋮				

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. The number-of-hops column only stores the hop count of the best paths between DS nodes.
3) The available bandwidth (B_a) of the necessary links to reach these dominators. Only the *best* B_a values are only stored, i.e. the *123hD* table *does not* store all possible 1-, 2-, and 3-hop paths.
4) The RIDs of the dominatee nodes on the paths to dominators within a 3-hop distance. These dominatees are referred to as connectors (if there is a need for any). Since at most two connectors are necessary to connect any two dominators within 3-hop distance, each entry in the connectors column of the *123hD* table has the format of a *pair* of RIDs. If no connectors are required, the entry pair will be (NULL, NULL). If only one connector is required, the pair will be (RID, NULL). If two connectors are needed, the pair takes the form of (RID_1, RID_2).
5) The expiry time of each table row.

D. 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 the main source of network dynamics. Maintenance is responsible to keep the QoS-VBBs continuously connected while node mobility is low or moderate. That is, if the 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 the proposed QoS-VBB construction algorithm, 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 QoS-VBB.

A detailed correctness analysis of the QoS-VBB is presented in [2].

5. Phase II: Assessment and Monitoring of QoS Metrics

Once the QoS-VBB is contructed, every dominatee node periodically assesses its QoS and initiates a unicast QoS message, which contains the measured QoS, to its dominator. The assessment phase relies on using a distance measurement system as published in [11]. Author's written permission of [11] was obtained prior to using the distance assessment sysetm as part of MMQoSMI. The system consists of four main processes: *windowing*, *normalisation*, *distance measurement* and *mapping*. See Figure 4.

For audio and videoconferencing multimedia applications, the three key parameters affect the overall QoS. These are *delay*, *jitter*, and *packet loss*. After measuring these parameters, they will be processed using a *windowing technique*, which means gathering every *m* consecutive packets in one window (block) and calculating their average delay, jitter, and packet loss. These parameters will be used as an input to the *data transformation step* of Figure 4. One weakness of the Minkowski distance function is that if an input element has relatively large values, then this value will dominate the other elements. Therefore, in this step, the distances were normalised by dividing the distance for each input attribute by specific numbers. These numbers represent the limits where the QoS will be poor. For videoconferencing, these limits were 600 msec for the delay, 30 msec for the jitter, and 3% for the packet loss. Similarly, for the audio, they were 600 msec for the delay, 5 msec for the jitter, and 6% for the loss. This was done in order to transform input data into a range which spans from 0 to 1. After transforming (normalising) the input

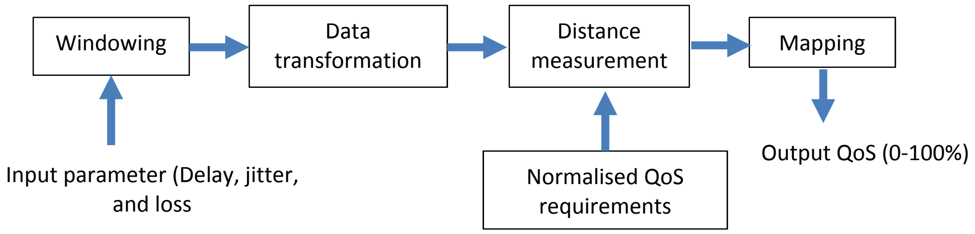


Figure 4. Distance Measurement System Block Diagram

(required and measured), the Minkowski distance calculations (distance measurement step in Figure 4) are carried out as illustrated in Equations 17 and 18. *X* values represent the actual measurements (measured delay, measured jitter, and measured loss) and the *Y* values represent required (desired) values (delay, jitter, and packet loss). The *Y* values are application dependent.

$$d_{XY}=\sqrt[\gamma]{\sum_{k=1}^{n}(X_i-Y_1)\gamma} \tag{17}$$

$$where\ Xi=[D_m, J_m, L_m]\ and\ Yi=[D_r, J_r, L_r]$$

$$Therefore, dxy=\sqrt[\gamma]{(D_m-D_r)^{\gamma}+(J_m-J_r)^{\gamma}+(L_m-L_r)\gamma}$$

$$dxy_{nor}=\sqrt[\gamma]{(\frac{D_m-D_r}{600})\gamma+(\frac{J_m-J_r}{30})\gamma+\frac{L_m-L_r}{3})\gamma},$$

where d_{XY} and d_{XYnor} are the regular and normalised distances respectively. D_m, J_m, L_m are the measured delays, jitter and loss, respectively. D_r, J_r, L_r are the required delays, jitter and loss, respectively.

The distance calculations of the measured values against the required values were carried out based on the acceptable QoS requirements (i.e., *delay* $\leq$ *150* msec, *jitter* $\leq$ *10* msec, and *packet loss* $\leq$ *1%*). Therefore, the normalised QoS requirement are (D_r = *150 msec*, J_r = *10 msec*, and L_r = 1%). Hence, Equation 17 becomes:

$$d_{\mathrm{XY\,nor}}=\sqrt[\gamma]{(\frac{D_m}{600}-0.25)\gamma+(\frac{J_m}{30}-0.33)\gamma+(L_m-0.33)\gamma}. \tag{18}$$

In order to convert the output of the distance measurement step value to a quantity that reflect the QoS or to an indictor of how the network dealt with the application, a transformation of the output calculated distance is required to a value in the range [0, 100]%. This was carried out in the mapping step of the Figure 4. Suppose that is selected to be 3, the situation at which the distance is minimum is when the measured QoS metrics are zeros (i.e., D_m = 0 msec, J_m = 0 msec, and L_m = 0%). Therefore, Equation 18 produces a distance $d_{\mathrm{XY\,nor}}$ = *-0.444*. This case represents the best case of network performance (i.e., QoS = 100%). The worst network performance is when the measured metrics are equal or greater than the poor values, i.e. when $D_m \geq$ 600msec, J_m > 30msec, and L_m > 3%. Hence, d_{XYnor} = 1.01 which corresponds to minimum poor QoS (i.e., QoS = 0). Therefore, we have two pairs of d_{XYnor} and QoS as (-0.444, 100%) and (1.01, 0%). Consequently, equation of a straight line can be prepared. Given that the line passes through the two points P1 = (x_1, y_1) (i.e., (-0.444, 100%)) and P2 = (x_2, y_2) (i.e., (1.01, 0%)), then the slope of the line is:

$$m = \frac{y_2 - y_1}{x_2 - x_1} \tag{19}$$

Given the slope *m* and a point P1 = (x_1, y_1), the relationship generally gets simplified to:

$$y = m(x - x_1) + y_1 \tag{20}$$

If *y* is replaced by QoS and *x* is replaced by the d_{XYnor} , Equation 20 can be rewritten as follows:

$$QoS = m * d_{XYnor} + c, \tag{21}$$

where *c* is constant which is equal to (y_1 - mx_1).
After calculating the slope (*m* = -68.75), Equation 21 becomes:

$$QoS = 69.75 – 68.75 * d_{Xynor.} \tag{22}$$

Similarly, when γ is selected to be 5 and following the same previous steps, the final equation will be:

$$QoS = 69.19 – 78.98 * d_{Xynor.} \tag{23}$$

In summary, after getting the QoS parameters, the parameters values will be used as inputs to the first stage of the QoS assessment system. After feeding the distance system by the QoS parameters, an output value will be produced which represents the evaluated QoS of each multimedia application. The measured QoS values will be in the range [0, 100]%. This output characterizes how the network dealt with the application.

Each dominatee (node) in the (CDS or MIS) should measure the QoS parameters (delay, jitter and loss) and then assess the instantaneous QoS based on the proposed distance assessment system. Every assessed QoS value should be reported in a unicast message to its dominator. The importance of the proposed monitoring system stems from the fact that dominatee nodes do not need to measure and submit each of the measured QoS parameters to the dominator node in a separated message. Instead, it just needs to send a single value (i.e., the assessed QoS) which represents the combined value of the measured QoS parameters. Because sending every instantaneous measured parameter to the dominator node will overwhelm the network and degrade its performance. Therefore, by gathering the measured QoS values from the dominatee nodes in every MIS, the QoS of every application can be monitored instantaneously. If different applications are running over the MANET, then different distance assessment system arrangement (requirements) should be identified depending on the nature of the multimedia application in terms of the QoS parameters that affect the behaviour of the given application.

6. Conclusions and Future Work

QoS monitoring over MANETs is one of their complicated and important issues. The major goals of this paper are of two fold: Firstly, to construct a stable VBB for MANETs. Secondly, to use this structure for QoS/performance monitoring of MANETs behaviour based on an intelligent measurement system. An *MMQoSMI* is introduced. *MMQoSMI* is a stability-aware QoS monitoring system. *MMQoSMI* requires each node to compute its own stability measure. The success of our monitoring system stems from the fact that its robustness is related to the reality that it utilizes a stability measure that predicts the network connectivity during its early construction stages for the purpose of constructing a stable QoS-VBB. 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 VBB construction. The maintenance issue is easily addressed by the algorithm's normal operation. The analytical results reveal attractive features.

The 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 dominator nodes 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 = jV j. Our future work includes the implementation of *MMQoSMI and t* extend the proposed QoS-VBB to deal with effective topology construction and routing. Additionally, future plans include the integration of multiple QoS in the formation of the QoS-VBB.

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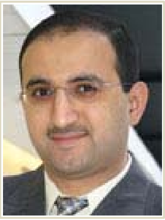

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