A Framework for Quality of Service in Mobile Ad Hoc Networks

Francis Ogwu[1], Mohammad Talib[1], Ganiyu Aderounmu[2], and Adedayo Adetoye[2]
[1]Department of Computer Science, University of Botswana, South Africa
[2]Department of Computer Science and Engineering, Obafemi Awolowo University, Nigeria

Abstract: *This paper presents a framework for specifying a probabilistic Quality of Service (QoS) guarantee in a mobile ad hoc network. The framework uses the mobility profiles of nodes in the network to establish probabilistic QoS. The network can deliver for a specified period of time. A mobility model was used to characterize the probabilities of path availability between two communicating nodes and QoS deliverable on the path. Mathematical models were developed for the probability of link and path availability, and bandwidth using continuous time stochastic mechanism. The proposed model was simulated using MATLAB version 5.2. The results of the research work show that the bandwidth guaranteed over a path diminishes with time, number of hops, and cell radius for a given mobility profile. Hence, a QoS-based routing algorithm can select more stable paths based on these metrics. This work provides a powerful paradigm for conception and dimensioning of the QoS deliverable by a MANET.*

Keywords: *Probabilistic QoS guarantee, MANET, path availability, QoS prediction.*

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1. Introduction

An ad hoc network is a collection of wireless mobile hosts forming a temporary network without the aid of any centralized administration or standard support services [1]. Advances in wireless technology and portable computing along with greater demands for user mobility are the major impetuses that will drive this class of self-organizing rapidly deployable networks to ubiquity [1, 11, 15, 13, 16, 19]. This network architecture will play increasingly important roles in commercial and military applications where instant network infrastructures would provide for example platforms for collaborative computing, military intelligence communications, access to wired networks or mobile access to the global.

Internet communication between arbitrary nodes in an ad hoc network requires routing over multiple-hop wireless paths. The length of a path that we define as the number of hops a packet has to traverse between the communicating nodes can vary drastically in an ad hoc network when compared with that of a fixed network. The major factors that affect the choice of path in a wired network include the current network load or traffic pattern and available buffer spaces in each router and the objectives of the routing algorithm; these may be fairly deterministic considering the fact that the network topology is fairly static. However, in mobile ad hoc network, the network topology is highly fluid due to links breaking and forming as a result of node mobility in the network. This can make routing very complex and non-deterministic in ad hoc networks. The number of hops traversed by packets in a session, network bandwidth, delay and jitter also change very drastically due to this variability introduced by the network mobility.

Furthermore, in this computing environment we would like applications to follow us around as we move from computing interface to interface, and from device to device [12, 18]. It therefore becomes important for us to be able to determine the Quality of Service (QoS) the network is able to deliver to these applications. Reliable message transfers with error control and notification of non-delivery is common in many modern communications systems. However, it is only this decade that much thought has been given to the ability to specify timeliness, and the perceived quality of the data arriving, particularly where more complex (multi-)media are being used. The underlying concepts of timeliness (including jitter), throughput, and reliability are the foundations of what is known as QoS [2, 8].

Different applications have QoS requirements that define minimum limits for their usefulness. Therefore, we would love to be able to guarantee the QoS the network can deliver to these applications. In doing this, we set to develop a framework for specifying the QoS deliverable based on the mobility patterns of the nodes in the network.

The research work in this paper will form frameworks that QoS-based routing algorithms can use in selecting paths for traffics during an application communication session. The framework is independent of the routing algorithm used or the clustering framework used in a mobile ad hoc network. It provides decision parameters that could be used in the design of routing algorithms based on a rigorous conception of the mobility behavior of large ad hoc networks, and provides a generic conception of the capacity and QoS deliverable by an ad hoc network. For example, the bandwidth that an ad hoc network can guarantee to two arbitrary communicating nodes within a specified period of time is a function of intermediate nodes' transport capacities and the probability of path availability between the nodes for that period.

2. Related Works

A probabilistic link availability model which can predict the future status of a wireless link was proposed in [4, 11]. In this model, nodes use the link availability as a metric to select more reliable neighbors to form stable clusters, the focus is on cluster formation and the stability of such clusters to facilitate intra-cluster and inter-cluster routing. The work proposed an adaptation of admission and connection control algorithms to support probabilistic QoS guarantees using the clustering framework as a future work.

A measure called "associativity" was proposed in [3, 4, 5, 7, 10, 14] as a new routing metric for link reliability. This metric tries to reflect the degree of the association stability between two mobile nodes through the connection stability of a node with respect to another one over time and space. It used a beaconing technique to classify a node's neighbor as "strongly" or "weakly" connected, hence the location stability of a neighbor is measured by directly relating it to the time its link has existed. The routing algorithm hence based its path selection on links that have existed for a period of time greater than a threshold. This technique therefore used measurement-based criteria that do not reflect the future status of the link to select paths. This makes the approach weak because historic and current link information may not indicate the future status of links because of the dynamic nature of MANET; the possible misjudgment to link reliability would drastically affect the network performance in high mobility environments. Our work looks at a QoS framework that can be incorporated into routing algorithms independent of the clustering technique, it also uses a prediction based model to indicate the future status of paths availability between communicating nodes.

3. Mobility Framework

We proposed an arbitrary ad hoc network with a random walk based mobility model. This model characterizes a mobile user, especially in a large ad hoc network where it will be unreasonable to keep detailed mobility profiles of each user. This random walk based model is a continuous-time stochastic process that characterizes mobility profiles of users in two-dimensional space.

Let us define $P^{k}_{m,n}(t_0 + t)$ as the path availability between two nodes n and m at time $t \geq t_0$. Hence, the probability of path availability [2] $\pi^{k}_{m,n}(t)$ is given by the following probability expression:

$$\pi^{k}_{m,n}(t) \equiv \Pr(P^{k}_{m,n}(t_0 + t) = 1 \mid P^{k}_{m,n}(t) = 1) \tag{1}$$

For the random walk based mobility model, each node's movement is a sequence of random length intervals called mobility epochs during which a node moves in constant direction at a constant speed. The node velocity varies from epoch to epoch. Each epoch i is characterized by a distance given by $D = V^{i}_{n}T^{i}_{n}$ and angle θ_n for a node n; where V^{i}_{n} is the speed during the ith epoch and T^{i}_{n} is the duration of the epoch. The number of epochs during an interval of length t is the discrete random process $\mathrm{N}_n(t)$.

The mobility profile of a node n moving according to the random ad hoc mobility model requires three parameters: λ_n, μ_n, and σ_n. The following list defines these parameters with the assumptions that were made in the model: The epoch lengths are identically, independently distributed (iid) exponentially with mean $\frac{1}{\lambda_n}$.

The direction of the mobile node during each epoch is iid uniformly distributed over (0, 2π) and remains constant only for the duration of the epoch. The speed during each epoch is an iid distributed random variable with mean μn and variance σ^{2}_{n} and remains constant only for the duration of the epoch. Speed, direction, and epoch length are uncorrelated. Mobility is uncorrelated among the nodes of a network, and links fail independently [11]. The epoch random mobility vector $\vec{R}^{i}_{n}$ represents the direction and distance moved by node n during mobility epoch i. It has magnitude $R^{i}_{n} = \left|\vec{R}^{i}_{n}\right| = V^{i}_{n}T^{i}_{n}$ which is the distance covered during the epoch and phase θ^{i}_{n} which is the direction of node n during epoch i.

The random mobility vector of node n is given by:

$$\vec{R}_n(t) = \sum_{i=1}^{i=N_n(t)} \vec{R}^{i}_{n} \tag{2}$$

For a mobile node with mobility profile $(\lambda_n, \mu_n, \sigma^2_n)$ with phase angle θ_n uniformly distributed over (0, 2π) as described above, the magnitude of the random mobility vector within t seconds is approximately Rayleigh distributed with parameter as follows:

$$\alpha_n = \frac{2t}{\lambda_n}\left(\sigma_n^2 + \mu_n^2\right) \qquad (3)$$

Also based on the theory of uniform random phasors:

$$\Pr(\theta_n \le \varphi) = \frac{1}{2\pi}\varphi \qquad 0 \le \theta \le 2\pi$$

and

$$\Pr(R_n(t) \le r) \approx 1 - e^{\left(\frac{-r^2}{\alpha_n}\right)}; \qquad 0 \le r \le \infty$$

We also define the joint node mobility vector $\vec{R}_{m,n}(t)$, which represents the equivalent random mobility vector of node m with respect to node n.

For two mobile nodes m, n moving with random ad hoc mobility profiles (λ_m, μ_m, σ^2_m) and (λ_n, μ_n, σ^2_n), respectively:

$$\vec{R}_{m,n}(t) = \vec{R}_m(t) - \vec{R}_n(t) \qquad (4)$$

which has magnitude $R_{m,n}(t)$ which is Rayleigh distributed with parameter $\alpha_{m,n} = \alpha_m + \alpha_n$ and the phase is uniformly distributed over (0,2π)

3.1. Link Availability Model

The path between two arbitrary nodes is typically made up of several links. Let $L_{m,n}(t)$ indicates the state of the link between nodes n and m at time t. $L_{m,n}(t) = 1$ if the link is active, $L_{m,n}(t) = 0$ if the link is inactive.
Link availability probability is given by:

$$A_{m,n}(t) = Pr\,(L_{m,n}(t_0 + t) = 1 \mid L_{m,n}(t_0) = 1) \qquad (5)$$

$A_{m,n}(t)$ gives the probability that a link will be active at time t_0+t given that the link is active at time t. This probability is a function of the node activation and link activation model. It is assumed that nodes activate and deactivate following an exponential distribution; the link activation distribution is derived below.

We proceed to find the link availability distribution; using Figure 1, first we derived the distance z that a mobile m must travel before getting out of perceivable transmission range of its neighbor n. That is, the distance from its current location (X_0,Y_0) to the boundary of the cell given its equivalent direction is $\theta_{m,n}$. We are thus considering the joint mobility vector $\vec{R}_{m,n}(t)$ of node m and n, fixing n as the frame of reference. If the effective radius of the cell is R_{eq} and m is initially located initially at an arbitrary point (X_0, Y_0) anywhere in the cell with equal probability; then the probability distribution function of the distance z is given by:

$$f_Z(z) = \frac{2}{\pi R_{eq}}\sqrt{R_{eq}^2 - \left(\frac{z}{2}\right)^2} \qquad 0 \le z \le 2R_{eq}$$

The equivalent direction of m ($\theta_{m,n}$) is uniform over (0, 2π), and the distance $R_{m,n}(t)$ moved in time t is approximately Rayleigh distributed, where m is assumed to activate within distance R_{eq} from n with equal probability. Assuming node m activates at point (X_0, Y_0) at time t_0, then the probability of link availability at time t is the probability that the equivalent distance that m travels in time t is less than the distance to the boundary of the approximating circle given by the distribution of Z. Hence[3, 14]:

$$A_{m,n}(t) = \Pr\,(R_{m,n}(t) < Z)$$

and $\Pr\,(R_{m,n}(t) < Z)$ =

$$1 - \left(1 + \frac{a}{b}z + \frac{a(a+1)z^2}{b(b+1)2!} + \sum_{k=3}^{\infty}\frac{(a)_k z^k}{(b)_k k!}\right) \qquad (6)$$

Expression 6 above is the hypergeometric series which is the series expansion for the Kummer Confluent Hypergeometric function Φ (a, b, z). The proof of 6 is as shown in Appendix 1-A.

Hence, by setting a = ½, b = 2, z = $-\frac{4R_{eq}^2}{\alpha_{m,n}}$

$$A_{m,n}(t) \approx 1 - \phi\left(\frac{1}{2}, 2, \frac{-4R_{eq}^2}{\alpha_{m,n}}\right) \qquad (7)$$

and

$$\alpha_{m,n} = 2t\left(\frac{\sigma_m^2 + \mu_m^2}{\lambda_m} + \frac{\sigma_n^2 + \mu_n^2}{\lambda_n}\right) \qquad (8)$$

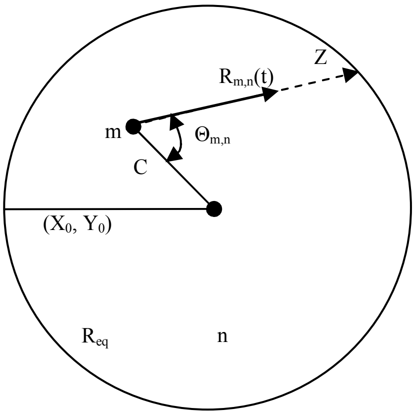

Figure 1. Derivation of link availability distribution for the node activation model.

3.2. Link Activation Model

A link becomes activated when an active node enters the circumference of a cell. Assuming an active node m enters the circumference of a cell at time t_0 such that m is located at a random point exactly R_{eq} from n with the direction of Z randomly and uniformly distributed over (0, π). Note Z should have a value of zero along any other trajectory; otherwise node m would never really enter the cell. Consequently, the probability distribution function of the distribution of Z is conditional with respect to $0 \leq \theta_{m,n} \leq \pi$ and is given by [3, 5, 14, 17]:

$$f_{Z|0\leq\theta_{m,n}\leq\pi}(z) = \frac{1}{\pi}.\frac{1}{\sqrt{R_{eq}^2 - \left(\frac{z}{2}\right)^2}} \qquad 0 \leq z \leq 2R_{eq}$$

The direction of node m is uniform over (0, 2π), whereas the direction of Z is uniform over (0, π). As a result, the conditional probability that defines the link availability is given as:

$$\begin{aligned} A_{m,n}(t) &= \Pr(R_{m,n}(t) < Z) \\ &= \Pr(R_{m,n}(t) < Z \mid 0 \leq \Theta_{m,n} \leq \pi).\Pr(0 \leq \Theta_{m,n}\ \pi) + \Pr(R_{m,n}(t) < Z \mid \pi \leq \Theta_{m,n} \leq 2\pi). \\ &\quad \Pr(\pi \leq \Theta_{m,n} \leq 2\pi) \end{aligned} \tag{9}$$

Using Figure 2, the conditional distribution of $R_{m,n}(t)$ for $0 \leq \Theta_{m,n} \leq \pi$ is determined as follows given that $\alpha_{m,n}$ is defined as in equation 8:

$$\Pr(R_{m,n}(t) < Z \mid 0 \leq \theta_{m,n} \leq 2\pi)$$

$$= 1 - I_0\left(\frac{-2R_{ea}^2}{\alpha_{m,n}}\right).e^{\left(\frac{-2R_{eq}^2}{\alpha_{m,n}}\right)} \tag{10}$$

Where I_0 is a modified Bessel's function of the first kind. The proof of 10 is as shown in Appendix 1-B.

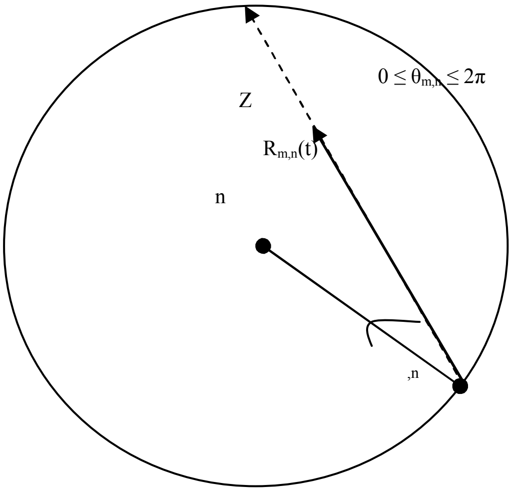

Figure 2. Derivation of link availability distribution for the link activation model.

The distribution of node m's trajectory is uniform over (0, 2π). Consequently, the probability that the trajectory is in the range of (0, π) is exactly 0.5. Also, since the value of Z over (π, 2π) is zero, the conditional probability $\Pr(R_{m,n}(t) < Z \mid \pi \leq \theta_{m,n} \leq 2\pi)$ is equal to zero. Based on these observations, (9) reduces to the following expression when combined with (10):

$$A_{m,n}(t) \equiv \Pr(R_{m,n}(t) < Z) = \tfrac{1}{2}\Pr(R_{m,n}(t) < Z \mid 0 \leq \theta_{m,n} \leq \pi)$$

$$= \frac{1}{2}\left(1 - I_0\left(\frac{-2R_{ea}^2}{\alpha_{m,n}}\right).e^{\left(\frac{-2R_{eq}^2}{\alpha_{m,n}}\right)}\right) \tag{11}$$

If $A_{i,j}(t)$ is the link availability for link (i, j) Є path k between nodes n and m. The probability of path availability at time t_0+t is denoted by $\pi_{m,n}^{k}(t)$. Considering that node mobilities are random and uncorrelated, the failure two adjacent links are independent; as a result, path availability is given by:

$$\begin{aligned} \pi_{m,n}^{k}(t) &= \Pr\left(P_{m,n}^{k}(t_0+t) = 1 \mid P_{m,n}^{k}(t_0) = 0\right) \\ &= \prod_{(i,j)\in k} A_{i,j}(t_0+t) \end{aligned} \tag{12}$$

3.3. Quality of Service Prediction

Given the percentage of time t that we have an end to end connection between the two arbitrary nodes n and m; we have a measure of the capacity C^k of path k that is available on an end to end basis within the period. Similarly, we can derive the end to end delay and jitter by considering the number of hops that constitute path k.

Assuming the expanse of the ad hoc network is a rectangular area of dimensions AxB square meters as shown in Figure 3, we desire to characterize the bandwidth given the number of hops n_k^{av} a packet would traverse from source to its destination.

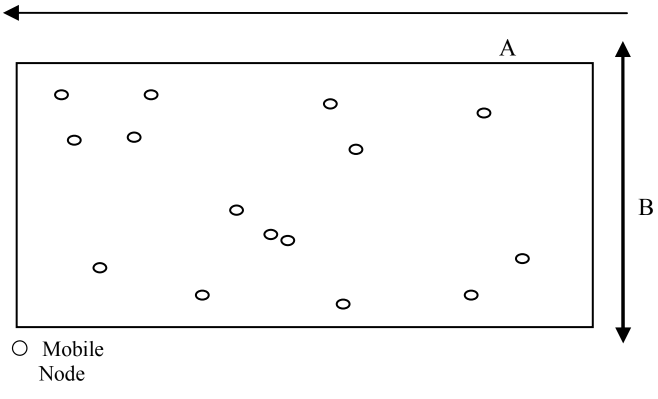

Figure 3. An ad hoc mobile network.

Hence, given the capacity of this path as C^k, the capacity actually delivered by this within the period t given the path is available at time t_0, thus:

$$C_D^k = C^k \prod_{l=1}^{n_k^{av}} \underset{(i,j)\in k}{\overset{l}{A}}(t) \tag{13}$$

Following Knuth's notation: f (n) = Θ (g (n)) denotes that f (n) = O (g (n)) as well as g (n) = O (f (n)), the throughput λ (n) obtainable by each node for a randomly chosen destination is:

$$\Theta\left(\frac{W}{\sqrt{n\log n}}\right)\text{bits/sec}$$

under non-interference protocol, given that the wireless network is made up of n identical randomly located nodes, each capable of transmitting at W bits/sec and using a fixed range [4].

Based on the protocol model, suppose node m at location X_i transmits to node n at location X_j, then this transmission is successfully received by n if

$$|X_k - X_j| \geq (1+\Delta)\,|X_i - X_j| \tag{14}$$

For every other node X_k sharing this wireless medium. The quantity $\Delta > 0$ models situations where a guard zone is specified by the protocol to prevent a neighboring node from interfering with the transmission. It also allows for imprecision in the achieved range of transmissions. Specifically, an upper bound for the transport capacity is $\sqrt{\frac{8}{\pi}}\frac{W}{\Delta}\sqrt{n}$ bit-meters/sec for every arbitrary network of all spatial and temporal scheduling strategies, while $\frac{W}{1+2\Delta}\frac{n}{\sqrt{n}+\sqrt{8\pi}}$ bit-meters/sec (for n a multiple of four) can be achieved when the nodes and traffic patterns are appropriately chosen, and the ranges and schedules of transmission are appropriately chosen. Here, one bit-meter represents when the network transports one bit a distance of 1 meter towards its destination [12]. These results can be used to derive the transport capacity of an arbitrary wireless network. A similar model in [4] is the physical model which uses physical layer considerations to determine the transport capacity of an arbitrary wireless network.

We thus have enough information to determine the probabilistic throughput that our network can deliver based on the mobility model proposed; this information can serve as a foundation for routing packets in an ad hoc mobile network. We can similarly derive the end to end delay in between the transmitting node and the destination. The value of this delay element increase with number of hops the packet traverses between its source and destination.

4. Numerical Result Analysis

The proposed model provides a rigorous framework for predicting the bandwidth deliverable by the ad hoc network. We considered a network with a fictitious upper bound of 10kbps on its link capacity. Similarly, a 2Mbps could be set for the network following the IEEE 802.11 specification for MAC layer protocol. Figure 4 shows the result of the bandwidth that the network can deliver to a node transmitting to another arbitrary node four hops away with each node moving with the same mobility profiles with mean speed of 2.5kph. The result is plotted for different effective transmission ranges used by the mobile nodes. The result shows the delivered bandwidth that can be guaranteed within a period of time t ranging from zero to 35 minutes diminishes rapidly with increasing t. Intuitively, this should be so, as the rate of link failures increases with time due to node mobility. Also, the rate of link failure is higher when the effective transmission radius becomes smaller. This is because a node located randomly within a cell would have to travel a smaller distance before experiencing a link failure. This is due to its traversal of the cell boundary. Lower transmission ranges hence can only sustain a link for a relatively lower duration before the link fails. This is because mobile nodes would move beyond their effective transmission radii more quickly.

Figure 5 shows the probabilistic bandwidth delivered by the network over a period of time given that the effective transmission radius is fixed at 1250 meters, a range reasonable for moderate power radio frequency transmitting device. The arbitrary nodes are separated by 4 hops and moving at various mean speeds ranging from 3.5kph to 5.5kph. It would be observed that the probabilistic bandwidth diminishes with increasing speed. This is attributed to the shorter period of time a node resides in a cell due to higher speeds before it goes beyond the cell and the link breaks. Hence, the system becomes more stable at low mean speed of the mobile nodes.

Finally, Figure 6 shows the variation of probabilistic bandwidth with number of hops that make up the communication path. The higher the number of hops that make up the path, the higher the probability of one link failing and therefore paths with more number of hops would deliver a lower aggregate bandwidth. It would also be observed that the higher hop systems have a higher rate of bandwidth drop; more hops imply higher chances of one breaking within a specified time period.

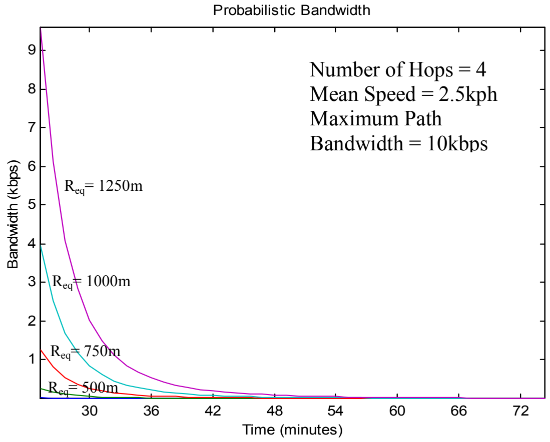

Figure 4. Bandwidth deliverable to a node transmitting to another arbitrary node.

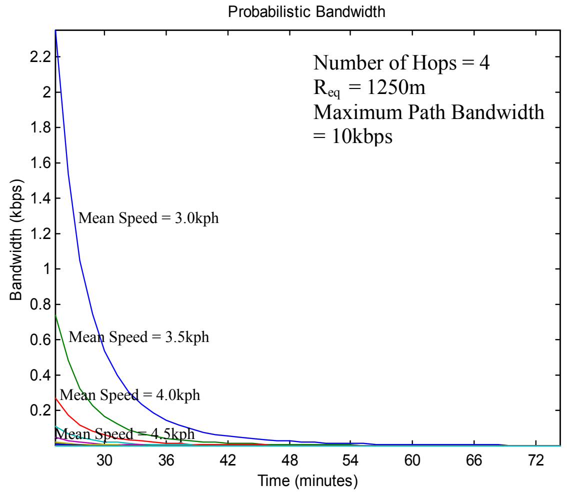

Figure 5. Probabilistic bandwidth delivered by a network over a period of time.

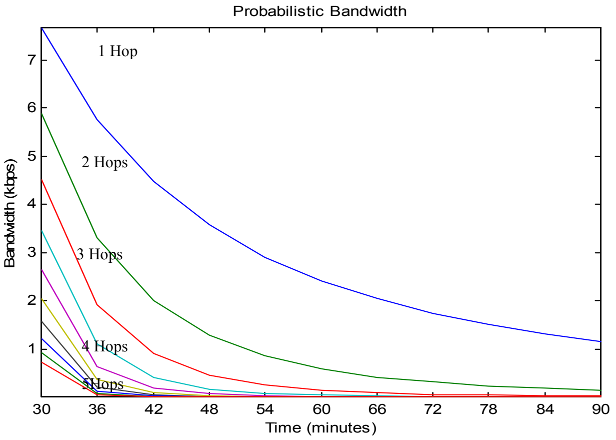

Figure 6. Variation of probabilistic bandwidth with numbers of hops.

5. Conclusion

In this paper, we presented a framework for specifying a probabilistic QoS guarantee in mobile ad hoc networks. To our knowledge, no other work has been published specifically treating probabilistic QoS guarantee based on the proposed mobility framework. Based on the model developed, expressions for link and path availability probability, and probabilistic bandwidth (a major QoS parameter) deliverable over a time period were derived. The framework could similarly be extended to predict other QoS parameters such as end to end delay, jitter, error, and packet loss.

The model developed was simulated using MATLAB version 5.2. Based on the result of the simulation, a QoS based routing algorithm would be able to select more stable paths to support a service and conceptually, it will also help network designers and engineers to select optimal operational metrics for the ad hoc network and provide a conceptual framework that can be used to evaluate the QoS deliverable under a specific mobility model. In future, we intend to develop a QoS routing algorithm based on the framework developed in this paper, furthermore, we intend to carry out performance evaluation of the new model and the existing schemes for QoS-based routing in ad hoc networks.

Appendix 1-A

$\Pr\ (R_{m,n}\,(t) < Z)$

$$= \int_{-\infty}^{\infty} \Pr\left(R_{m,n}\left(t\right) < Z \mid Z = z\right) f_Z(z)dz$$

$$= \int_{-\infty}^{\infty} \Pr\left(R_{m,n}\left(t\right) < z\right) f_Z(z)dz$$

$$= \int_0^{2R_{eq}} \left(\left(1 - e^{-\frac{z^2}{\alpha_{m,n}}} \right) \frac{2}{\pi R_{eq}^2} \sqrt{R_{eq}^2 - \left(\frac{z}{2}\right)^2} \right) dz$$

$$= 1 - \int_0^{2R_{eq}} \frac{2}{\pi R_{eq}} \sqrt{R_{eq}^2 - \left(\frac{z}{2}\right)^2} \left(\sum_{i=0}^{\infty} (-1)^i \frac{z^{2i}}{i!\alpha_{m,n}^i} \right) dz$$

$$= 1 - \left(1 - \frac{R_{eq}^2}{\alpha_{m,n}} + \frac{R_{eq}^4}{\alpha_{m,n}^2} - \frac{5R_{eq}^6}{6\alpha_{m,n}^3} + \ldots \right)$$

Appendix 1-B

$\Pr\ (R_{m,n}\ (t) < Z \mid 0 \le \theta_{m,\,n} \le 2\pi)$

$$= \int_{-\infty}^{\infty} \Pr\left(R_{m,n}(t) < Z \mid Z = z\right) f_{Z|0\le\theta_{mn},\le\pi}(z)dz$$

$$= \int_{-\infty}^{\infty} \Pr\left(R_{m,n}(t) < Z \mid Z = z\right) f_{Z|0\le\theta_{mn},\le\pi}(z)dz$$

$$= \int_0^{2R_{eq}} \frac{1}{\pi} . \frac{1 - e^{\frac{-z^2}{\alpha_{m,n}}}}{\sqrt{R_{eq}^2 - \left(\frac{z}{2}\right)^2}} dz$$

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Francis Ogwu has been working as a senior lecturer in the Department of Computer Science at the University of Botswana for the last seven years. He is also an adjunct associate professor at TU International, USA. He has acted as the head of the Department of Computer Science at the University of Botswana, Botswana, on several occasions. He has been the head of the Department of Computer Science and Engineering at Obafemi Awolowo University Ile-Ife, Osun State, Nigeria. He has published over 31 research papers in international journals and conferences. He has also been the member of the editorial board for Botswana Journal of Technology (BJT), South African Computer Lecturers Association (SACLA), and IASTED Canada. He has chaired various IASTED conferences and SALCA'05. His areas of interest are computer communications, networking, artificial intelligence, speech processing, and smellography.

Mohammad Talib is a senior lecturer in the Department of Computer Science at the University of Botswana and an adjunct associate professor at the TU International, USA. He has an excellent industrial relevance and has worked as software engineer at CA, USA for a significant period of time. He has been a consultant for several software development companies and handled various small and big projects in India and abroad. He was conferred upon the degree of the Doctor of Philosophy in computer science with specialization in computer vision from the Prestigious University of Lucknow in India with Certificate of Honors. Besides PhD, he is also flanked by an MSc in computer science, MSc in statistics and PG Diploma in Computing. He has supervised over a dozen Master and four PhD students in different areas of computer science, business and IT. His research areas include bioinformatics, computer vision, and robotics. Currently, he is working on a two way interactive video communication through the virtual screen with the essence of smellography. He has over forty five research papers published in different international journals and conference proceedings besides a book in his academic account.

Ganiyu Aderounmu is a senior lecturer and head of Department of Computer Science and Engineering at Obafemi Awolowo University Ile-Ife, Nigeria. He has first degree in computer science, followed by a second degree, and a PhD in computer communications and networking from the Computer Science Department of Obafemi Awolowo University. His area of interests is computer communications and networking. He has quite number of significant years of experience in the same area.

Adedayo Adetoye is a lecturer in the Department of Computer Science and Engineering at Obafemi Awolowo University, Ile-Ife, Nigeria. He obtained his MSc in computer communications and networking from the same university. He has numerous papers published in different journals of international repute. His area of interest includes computer communication, networking, and computer architecture.