A Mobility Measure for Mobile Ad-Hoc Networks

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Abstract— **A mobility measure for mobile ad-hoc networks is proposed that is flexible because one can customize the definition of mobility using a *remoteness function*. The proposed measure is consistent because it has a linear relationship to the rate at which links are established or broken for a wide range of mobility scenarios, where a scenario consists of the choice of mobility model, the physical dimensions of the network, the number of nodes. This consistency is the strength of the proposed mobility measure because the mobility measure reliably represents the link change rate regardless of network scenarios.**

Index Terms— **MANET, mobility, routing protocol.**

I. INTRODUCTION

The performance of a mobile ad hoc network (MANET) in terms of throughput, latency, and scalability is related to the efficiency of the routing protocol in adapting to changes in the network topology due to mobility of the nodes [1], [2]. Signaling overhead traffic for maintenance of routes for a MANET is proportional to the rate of such link changes, which in turn is a function of the mobility of the nodes. Therefore, for assessing different routing protocols for MANETs, it is important to use models for mobility and to have some index or quantitative measure of mobility that is *relevant* to the performance of the network [3]. We introduce a measure of mobility that focuses on the effect of mobility on link changes and thereby is useful for comparative studies of MANET routing protocols.

Several mobility models have been proposed for simulation of the movement of nodes in a MANET [4], [5], [6], [7], [8]. These models can be classified into two groups: stochastic models, and event-based models that simulate particular events such as conferences. Regardless of the selection of a mobility model, being able to measure the amount of mobility is as important as the realism of the model itself. To date, however, little effort has been made to quantify the degree of mobility of the nodes in ad-hoc networks. Instead, its poor substitutes have been used in many studies. For example, in [4], [5] the average speed of the nodes is used to represent their mobility, while the maximum speed is used in [3]. The problem with using average or maximum speed as a measure of mobility is that the relative motion between the nodes is not reflected in such a measure; also, using the same average or maximum speed in different mobility models or in networks with different physical dimensions often leads to different rates of route changes. In [1] and [2], the performance of different routing protocols are compared using simulation with the random waypoint model, where the "pause time" is used to represent the degree of node mobility. However, the pause time is a parameter unique to the random waypoint model, and it is not the only parameter that affects the mobility in this model. In [7], the link change rate itself is used as a measure of mobility; this approach is not satisfactory because it does not represent mobility in physical terms—what is needed is a measure of mobility that reliably represents the link change rate.

Larsson et al. [9] make a significant improvement to this situation by recognizing that not all node movement is relevant to MANET routing protocol assessment—for example, if all the nodes are moving at the same speed and in the same direction, the motion does not affect network topology. They define a "mobility factor" that takes into account the relative motions of nodes, and show how the mobility factor is related to the link change rate for a particular mobility model. However, we have found that the relationship of mobility factor to the link change rate is inconsistent for different mobility models.

In this letter, we introduce a mobility measure that is flexible and consistent. It is flexible because one can customize the definition for relevant mobility using a *remoteness function* for a given application. It is consistent because the mobility measure has the same linear relationship to the link change rate for a wide range of mobility scenarios, where a scenario consists of the choice of mobility model, the physical dimensions of the network, the number of nodes. This consistency is the strength of the proposed mobility measure because the link changes and thus the routing overhead are reliably reflected in the mobility measure.

II. THE CONCEPT OF REMOTENESS

Let $\mathbf{n}_i(t)$, $i = 0, 1, \cdots, N-1$, represent the location vector of node i at time t. Then $d_{ij}(t) = \mid \mathbf{n}_j(t) - \mathbf{n}_i(t) \mid$ is the distance from node i to node j at time t. We define the *remoteness* of node i from node j at time t as follows:

$$\mathcal{R}_{ij}(t) = F(d_{ij}(t)), \tag{1}$$

where $F(\cdot)$ is a function of the distance. The simplest choice for $F(\cdot)$ is the identity function, that is, the remoteness is simply the distance between the nodes. However, in applications such as MANET, a more sophisticated definition of remoteness is more useful. For example, with a mobile node with communication range R, a node located at a distance of three times R can be considered as remote as a node located at a distance of ten times R. Similarly, if a node is well within the communication range R, the node would not seem very remote even if the distance were doubled. On the other hand, if a node is in the vicinity of the communication range R, the subjective remoteness of the node will dramatically vary as the node moves in or moves away. In the light of these observations, we require that $F(\cdot)$ satisfy the followings:

a) $F(0) = 0$, $\lim_{x\to\infty} F(x) = 1$;
b) $\frac{dF(x)}{dx} \geq 0$ for all $x \geq 0$;
c) $\frac{dF(x)}{dx} \mid_{x=0} = 0$;
d) $\lim_{x\to\infty} \frac{dF(x)}{dx} = 0$;

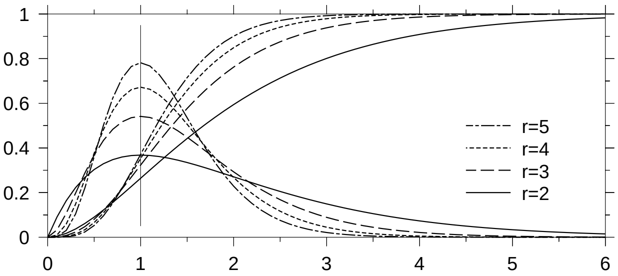

Fig. 1. Plots of Gamma cdf and pdf functions for $r = 2, 3, 4, 5$, where $\lambda = (r-1)/R$ and $R = 1$.

e) $\frac{dF(x)}{dx} \mid_{x=R} \geq \frac{dF(x)}{dx}$ for all $x \geq 0$.

(a) normalizes $F(\cdot)$ to have unity maximum value. (b) guarantees that the remoteness is a monotonically increasing function of distance, and as a result $0 \leq F(\cdot) \leq 1$ from (a). (c) and (d) give the boundary condition of $F(\cdot)$, which guarantee that the remoteness of a node at extreme locations does not change with the movement of the node. Finally, (e) makes the remoteness most sensitive to the movement of a node at communication range. A function that satisfies all of the requirements is the gamma cumulative distribution function (cdf) with $\lambda = (r-1)/R$:

$$F(x) = \frac{1}{\Gamma(r)} \int_0^x \lambda e^{-\lambda\tau} (\lambda\tau)^{r-1} d\tau, \quad x \geq 0,\ r \geq 2. \qquad (2)$$

As shown in Fig. 1, larger r means more dramatic change of remoteness at the communication range. As a result, we can give more emphasis on the movement of the nodes at and near the communication range by choosing larger r.

Any function that satisfies the above requirements can be used to define the remoteness. By choosing $F(x)$ with higher slope at R (larger r in the case of the gamma cdf), the resulting mobility measure proposed in the following section will have better consistency. However, the mobility measure will loose its sensitivity to the movements of the nodes in distance, which can be an undesired result in some applications.

III. THE PROPOSED MOBILITY MEASURE

As the nodes move, the remoteness changes in time. Thus, we define the *mobility measure* $M(t)$ of a wireless network in terms of the time derivatives of the remoteness as follows:

$$M(t) = \frac{1}{N} \sum_{i=0}^{N-1} M_i(t), \qquad (3)$$

where N is the number of nodes and

$$M_i(t) = \frac{1}{N-1} \sum_{j=0}^{N-1} \left| \frac{d}{dt} F(d_{ij}(t)) \right|. \qquad (4)$$

$M_i(t)$ is a measure of the relative movement of other nodes as seen by node i. Thus, $M(t)$ represents the *average amount* of the movement of the nodes in the network at time t. In steady state, we can use the time average of $M(t)$ defined as follows:

$$M = \frac{1}{T} \int_0^T M(t) dt.$$

If $F(\cdot)$ in (2) is used, then (4) becomes

$$M_i(t) = \frac{1}{N-1} \sum_{j=0}^{N-1} \mid d'_{ij}(t) \cdot f(d_{ij}(t)) \mid, \qquad (5)$$

where $f(\cdot)$ is the gamma probability density function (pdf). Note that (5) is a function of the time derivative of the distance weighted by a function of the distance. As shown in Fig. 1, since $f(x)$ has small values for $x \ll R$ or $x \gg R$, and has its maximum at $x = R$, the movements of the nodes around the communication range R is emphasized. Taking advantage of the distance information, $M(t)$ is suitable for applications involving MANETs in a multi-hop network application.

IV. SIMULATION

The mobility measure M is a normalized quantity (see (3) and (4)). In a network with N nodes, since there are total of ${}_NC_2 = \frac{N(N-1)}{2}$ node pairs (the maximum possible number of links), M multiplied by $\frac{N(N-1)}{2}$ reflects the actual link change rate in the entire network. In this section, we evaluate the consistency of the proposed mobility measure by comparing $\frac{N(N-1)}{2}M$ with the link change rate.

a) Network scenarios: We use a variety of network scenarios in steady state based on widely used stochastic mobility models to evaluate the proposed mobility measure. The mobility models used are the *random waypoint mobility* (RWP) model, the *random Gauss-Markov* (RGM) model [4], and the *reference point group mobility* (RPGM) model [8].

Two different types of network scenarios are used to evaluate the proposed mobility measure. In all simulations, a normalized communication range $R = 1$ is used. For both RWP and RGM models, the minimum speed $V_{\min} = 0.1$ and the maximum speed $V_{\max} = 1$ are used. For the RGM model, the speed v and the direction θ of a node are updated every $\Delta t = 0.2$ seconds, where Δv and $\Delta\theta$ are of uniform distributions $U[-0.1, 0.1]$ and $U[-0.1\pi, 0.1\pi]$, respectively.

The first type of network scenario involves a group of nodes randomly moving in a square region. By various combinations of the mobility model, dimension of the region, number of nodes N, pause time (in the case of the RWP model), a variety of network scenarios is generated as shown in Fig. 2(a). For example, scenario S6 has 40 nodes moving in RWP model with pause time 2.0 seconds in 6×6 square region. The second type of network scenario uses the RPGM model moving in 6×6 square region. For the trajectory of the logical center of each group, the RWP model is used with $V_{\min} = 0.1$, $V_{\max} = 1$, and pause time of uniform distribution $U[0, 5]$. The update interval $\tau = 1$ is used for the random motion vector. Fig. 2(b) summarizes the type 2 network scenarios. In scenario G1, there are 5 groups each consisting of 7 nodes (total 35 nodes). One of the reference points of the nodes is located at the logical center of each group, and the other 6 reference points are located at the corners of a regular hexagon centered at the logical center with the length of its side 0.25. The length of the random motion vector has a uniform distribution $U[0, 0.25]$, that is $\text{RM}_{\max} = 0.25$. Scenario G2 has 7 groups each consisting of 5 nodes (total of 35 nodes). All reference points of the 5 nodes are located at the logical center of each

	RWP				RGM	
	network dimension	N	pause time		network dimension	N
S1	6×6	$\mathbf{30}$	0	T1	6×6	$\mathbf{30}$
S2	$\mathbf{6 \times 6}$	$\mathbf{40}$	$\mathbf{0}$	T2	$\mathbf{6 \times 6}$	$\mathbf{40}$
S3	6×6	$\mathbf{50}$	0	T3	6×6	$\mathbf{50}$
S4	$\mathbf{5 \times 5}$	40	0	T4	$\mathbf{5 \times 5}$	40
S5	$\mathbf{4 \times 4}$	40	0	T5	$\mathbf{4 \times 4}$	40
S6	6×6	40	$\mathbf{2}$			
S7	6×6	40	$\mathbf{4}$			

(a) Type 1: a group of randomly moving nodes in a square region.

	Description
G1	5 groups, 7 nodes/group (total 35 nodes), $\mathrm{RM}_{\max} = 0.25$ (small intra-group motion),
G2	7 groups, 5 nodes/group (total 35 nodes), $\mathrm{RM}_{\max} = 0.5$ (large intra-group motion),

(b) Type 2: group mobility models.

Fig. 2. Network scenarios.

group. Scenario G2 allows more intra-group motion compared to scenario G1 by having $\mathrm{RM}_{\max} = 0.5$.

b) Simulation results: For each network scenario, the average link change rate is compared with the mobility measures. 100 seconds of simulation were run for each scenario in type 1, and 500 seconds of simulation time was used for each scenario in type 2. The mobility measure $M(t)$ was taken every 0.01 seconds, and averaged in time to obtain M.

Fig. 3(a) shows the simulation results with $r = 3$. For type 1 scenarios with RWP or RGM model, $M\frac{N(N-1)}{2}$ and the link change rate show a good linear relationship for the changes in the number of nodes N (S1–S2–S3, T1–T2–T3), the physical dimension of the network (S2–S4–S5, T2–T4-T5), and the pause time (in the case of the RWP model) (S2–S6–S7) . A good linear relationship is also observed for the network scenarios with group mobility model.

By using larger r, we can give more weight to the movements of the nodes near the communication range R. Fig. 3(b) shows the simulation results with $r = 5$. The relationship between the link change rate and $M\frac{N(N-1)}{2}$ is even more linear than it is observed in Fig. 3(a). While this is a desirable property, one possible drawback of using larger r is that the mobility measure loses its sensitivity to the movements of nodes in distance.

V. CONCLUSION

In this letter, we introduced a canonical mobility measure for mobile ad hoc networks which is flexible and consistent for a wide range of scenarios. The consistency of the mobility measure was demonstrated by the simulation results, which showed the ability of the mobility measure to reliably predict the link changes for various simulation scenarios. The proposed mobility measure provides a unified means of measuring the degree of mobility in a MANET. However, the flexibility of the scheme of the proposed mobility measure makes it useful for applications other than MANETs.

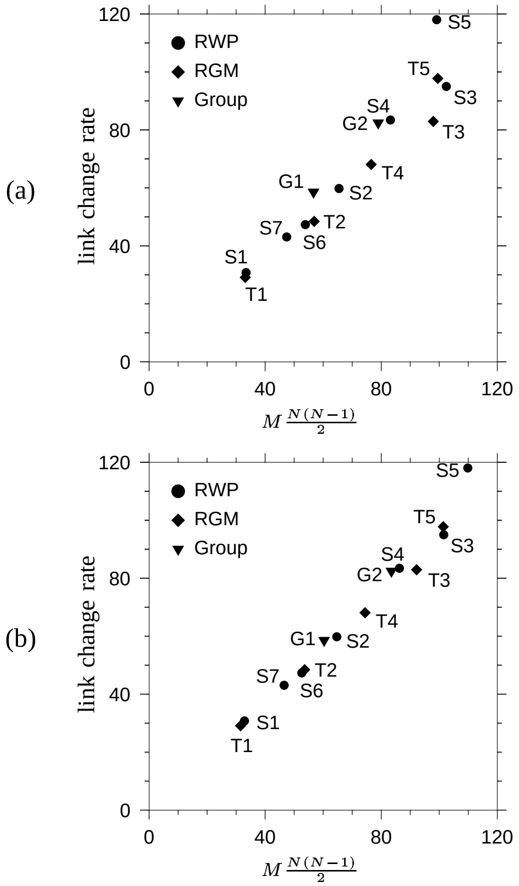

Fig. 3. Link change rate vs. $M\frac{N(N-1)}{2}$: (a) $r = 3$, (b) $r = 5$.

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