

## PAPER

# A Standard Measure of Mobility for Evaluating Mobile Ad Hoc Network Performance

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**SUMMARY** The performance of a mobile ad hoc network (MANET) is related to the efficiency of the routing protocol in adapting to changes in the network topology and the link status. However, the use of many different mobility models without a unified quantitative “measure” of the mobility has made it very difficult to compare the results of independent performance studies of routing protocols. In this paper, a mobility measure for MANETs is proposed that is flexible and consistent. It is flexible because one can customize the definition of mobility using a *remoteness function*. It is consistent because it has a linear relationship with the rate at which links are established or broken for a wide range of network scenarios. This consistency is the strength of the proposed mobility measure because the mobility measure reliably represents the link change rate regardless of network scenarios.

**key words:** *mobility measure, mobile ad-hoc network, mobility model, routing protocol*

## 1. Introduction

A mobile ad hoc network (MANET) is an autonomous system of mobile nodes connected by wireless links. In a MANET, it is assumed that the nodes are free to move randomly while being able to communicate with each other, often over multi-hop links, without the help of a fixed network infrastructure. Due to the mobility of the nodes, the network topology may change unpredictably leading to changes of wireless link status between nodes. The movement of a node out of, or into, the communication range of other nodes changes not only its neighbor relationships with those other nodes, but also all routes based on the relationships. Signaling overhead traffic for maintenance of routes for a MANET is proportional to the rate of such link changes. Thus the performance of a MANET is closely related to the efficiency of the routing protocol in adapting to changes in the network topology and the link status [1], [2].

A number of routing protocols for MANET have been proposed and many performance studies of the routing protocols are also available. Since, few MANETs have been deployed, most of these studies are simulation based. For performance evaluation of a routing protocol for a MANET using simulation, it is imperative to use an appropriate mobility model to simulate the motion of the nodes in a network, and many

mobility models for MANET have been developed to meet this needs [3]–[7]. However, the use of many different mobility models without a unified quantitative “measure” of the mobility has made it very difficult to compare the results of independent performance studies of routing protocols. For example, assume A evaluates the performance of routing protocol R1 using mobility model M1, and B evaluates the performance of routing protocol R2 using mobility model M2. Since two different mobility models are used, it is very difficult to draw a conclusion of which routing protocol performs better from the results of A and B. Thus, to make the comparison possible, it is necessary to have some index of quantitative mobility measure of the network.

However, in studies published to date, there is no unified approach for quantifying the degree of mobility. For example, in [3] and [4] the average speed of the nodes is used to represent their mobility, while the maximum speed is used in [8]. 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 performances 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 [6], the rate of link changes itself is used as a measure of mobility; in our view, this approach is not satisfactory because link change does not represent mobility in physical terms. Furthermore, as shown in Sect. 6, it is tricky to calculate an accurate estimation of the link change rate when the network is not in steady state.

The authors of [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. By defining a “mobility factor” that takes into account the relative motions of nodes, they show how this mobility factor

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is related to the number of link changes for a particular mobility model. However, among other drawbacks which we discuss below, we have found that the relationship of the mobility factor to the number of link changes is not the same for different mobility models. In [10], the influence of the patterns of node mobility to the routing protocol is also recognized and several protocol independent metrics are proposed to differentiate between different mobility patterns. However, the maximum speed of nodes is used as a measure of mobility in [10].

In this paper, we introduce a mobility measure for MANET that is “standard” in that it is flexible and consistent. It is flexible because one can customize the mobility measure using a *remoteness function* proposed in this paper. It is consistent because the mobility measure has a linear relationship with link change rate for a wide range of network scenarios. Since the link change reflects the change of network topology and affects the overall performance of the network, having a consistent linear relationship with the link change rate is a very important attribute of a mobility measure.

This paper is organized as follows. In Sect. 2, we introduce the concept of the *remoteness* of nodes. Then we propose a mobility measure using the concept of remoteness in Sect. 3. In Sect. 4, some widely used mobility models for MANET are introduced. These mobility models are used in Sect. 5 to develop various network scenarios for simulation. In Sect. 6, simulation results for various wireless network scenarios are shown and the consistency of the proposed mobility measure is evaluated. Section 7 is the conclusion of this paper.

## 2. The Concept of Remoteness

Let  $\mathbf{n}_i(t)$ ,  $i = 0, 1, \dots, N - 1$ , represent the location vector of node  $i$  at time  $t$ . Define  $d_{ij}(t) = |\mathbf{n}_j(t) - \mathbf{n}_i(t)|$  as the distance from node  $i$  to node  $j$  at time  $t$ . Then, the *remoteness* of node  $i$  from node  $j$  at time  $t$  is defined as

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

where  $F(\cdot)$  is a function of the distance. The simplest choice for  $F(\cdot)$  is the identity function, that is, the remoteness is just the distance between the nodes. However, in applications such as MANET, a more sophisticated definition of remoteness is more useful. For example, with a wireless 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 movement of the node may change the wireless link status with the node. In the light of

these observations, we require that  $F(\cdot)$  satisfy:

- a.  $F(0) = 0, \lim_{x \rightarrow \infty} F(x) = 1$ ;
- b.  $\frac{dF(x)}{dx} \geq 0$  for all  $x \geq 0$ ;
- c.  $\frac{dF(x)}{dx} |_{x=0} = 0$ ;
- d.  $\lim_{x \rightarrow \infty} \frac{dF(x)}{dx} = 0$ ;
- e.  $\frac{dF(x)}{dx} |_{x=R} \geq \frac{dF(x)}{dx}$  for all  $x \geq 0$ .

Requirement (a) normalizes  $F(\cdot)$  to have unity maximum value. Requirement (b) guarantees that the remoteness is a monotonically increasing function of distance, and as a result  $0 \leq F(\cdot) \leq 1$  from (a). Requirements (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, requirement (e) makes the remoteness most sensitive to the movement of a node at communication range.

One of the functions that satisfy all of the requirements is

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

with  $\lambda = (r - 1)/R$ , where  $r$  can be a non-integer. Note that  $F(x)$  is the cumulative distribution function (cdf) of a gamma random variable with parameter  $r$ , and thus

$$f(x) = F'(x) = \frac{1}{\Gamma(r)} (\lambda x)^{r-1} \lambda e^{-\lambda x}. \tag{3}$$

Figure 1 shows plots of  $F(x)$  and its derivative  $f(x)$  for various values of  $r$ , where the communication range  $R$  is normalized to unity. As shown in the figure, 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  $r$ .

Note that (2) is only one of many possible choices

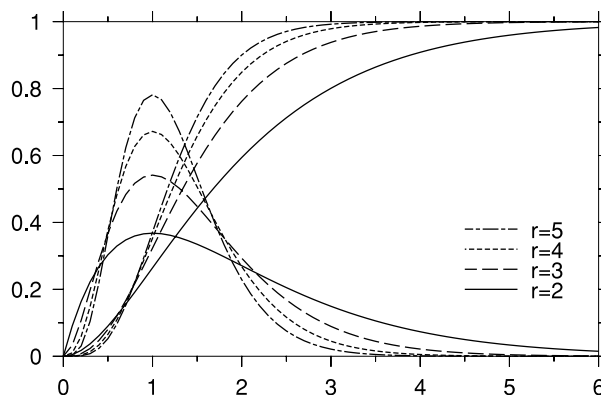


Fig. 1 Plots of gamma cdf and pdf functions for  $r = 2, 3, 4, 5$ , where  $\lambda = (r - 1)/R$  and  $R = 1$ . ( $F(x)$  and  $f(x)$  in (2) and (3))

of  $F(x)$ . Any function that satisfies the above requirements can be used to define the remoteness, which constitutes the flexibility of the proposed mobility measure.

### 3. The Proposed Mobility Measure

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

$$M(t) = \frac{1}{N} \sum_{i=0}^{N-1} M_i(t), \quad (4)$$

where  $N$  is the number of nodes and

$$M_i(t) = \frac{1}{N-1} \sum_{j=0}^{N-1} \left| \frac{d}{dt} F(d_{ij}(t)) \right|. \quad (5)$$

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

$$M = \frac{1}{T} \int_0^T M(t) dt. \quad (6)$$

If we choose  $F(\cdot)$  defined in (2), then

$$M_i^G(t) = \frac{1}{N-1} \sum_{j=0}^{N-1} M_i^G(t), \quad (7)$$

where the superscript ‘‘G’’ means ‘‘gamma,’’ and

$$M_i^G(t) = \frac{1}{N-1} \sum_{j=0}^{N-1} |d'_{ij}(t) \cdot f(d_{ij}(t))|, \quad (8)$$

$d'_{ij}(t)$  = the time derivative of  $d_{ij}(t)$ .

On the other hand, if we choose the *identity* function for  $F(\cdot)$ , the mobility measure can be written as

$$M_i^I(t) = \frac{1}{N-1} \sum_{j=0}^{N-1} M_i^I(t), \quad (9)$$

where the superscript ‘‘I’’ means ‘‘identity,’’ and

$$M_i^I(t) = \frac{1}{N-1} \sum_{j=0}^{N-1} |d'_{ij}(t)|. \quad (10)$$

$M_i^G(t)$  and  $M_i^I(t)$  are both mobility measures normalized by the number of nodes  $N$ , and *continuous functions* of time that represent the quantitative measures of the *relative* motion between nodes at time  $t$  rather than the absolute motion. Note that (8) 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

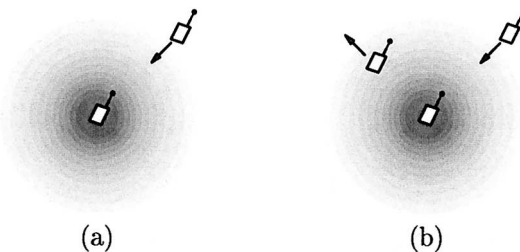


Fig. 2 Two simple wireless networks.

small values for  $x \ll R$  or  $x \gg R$ , and has its maximum at  $x = R$ , the movements of the nodes around the vicinity of the communication range  $R$  is emphasized. That is,  $M^G(t)$  takes advantage of the distance information between the nodes and suitable for applications such as MANET, a multi-hop wireless network where the communication range is an important factor of the network. However, the identity function does not satisfy the requirements given in Sect. 2. Thus, (10) is simply a function of the time derivative of the distance between nodes, and  $M^I(t)$  represents a normalized total amount of the relative movement of the nodes in the entire network and is inappropriate for applications with multi-hop wireless links.

The mobility factor defined in [9] is similar to  $M^I$ , the time average of  $M^I(t)$ , but unlike  $M^I$ , it may give wrong information in some cases. For example, in Fig. 2, the simple network illustrated in (a) has higher mobility factor than the network illustrated in (b), while in fact the network in (b) has more node movement. This undesirable result is because the terms corresponding to the movements of the two nodes in (b) are combined linearly and cancel out each other in the calculation of the mobility factor.

### 4. Mobility Models

One of the essential characteristics of a good mobility measure is *consistency*. We use a variety of network scenarios based on widely used stochastic mobility models to evaluate the consistency of the proposed mobility measure. The mobility models used are the *random waypoint mobility model* [1], the *random Gauss-Markov model* [3], [4], and the *reference point group mobility model* [7].

In the random waypoint (RWP) model, a node selects a random destination uniformly distributed over a predefined region and moves to the destination at a random speed uniformly distributed between the minimum and maximum speed. Reaching the destination, after pausing for a certain period of time, the node selects a new random destination and speed.

In the random Gauss-Markov (RGM) model, each node is assigned a speed  $v$  and direction  $\theta$ , and  $v$  and  $\theta$  are updated every  $\Delta t$  as follows:

$$v(t + \Delta t) = \min[\max(v(t) + \Delta v, V_{\min}), V_{\max}],$$

$$\theta(t + \Delta t) = \theta(t) + \Delta\theta,$$

where  $V_{\min}$  and  $V_{\max}$  are the minimum and maximum speed of the node, and  $\Delta v$  and  $\Delta\theta$  are random variables with uniform distribution over the intervals  $[-\Delta v_{\max}, \Delta v_{\max}]$  and  $[-\Delta\theta_{\max}, \Delta\theta_{\max}]$ , respectively. When a node reaches a boundary, the node reflects off the boundary by choosing a new random direction. However, the updates of the  $v$  and  $\theta$  can be implemented in various ways. For another example of the implementation of the RGM model, see [4].

In the reference point group mobility (RPGM) model, each group of nodes has a logical center, which defines the group's motion behavior such as location, speed, direction, etc. Thus, the trajectory of a group is determined by the trajectory of its logical center, which is given by a sequence of check points. As time goes by, the logical center of a group keeps moving from one check point to the next. In addition to the logical center, the RPGM model defines a reference point and a random motion vector for each node in a group. A reference point is a point about which a node moves in random fashion, and is pre-defined for each node with respect to the logical center. The random motion of a node is determined by a random motion vector, which represents the random deviation of a node from the reference point. The random motion vector is updated periodically and is given by the length and the direction which have uniform distributions over the intervals  $[0, RM_{\max}]$  and  $[0, 2\pi)$ , respectively. Let  $\mathbf{n}(t_0)$  be the location vector of a node of the RPGM model at  $t = t_0$ ; then

$$\mathbf{n}(t_0) = \mathbf{c}(t_0) + \vec{RP} + \vec{RM}(t_0), \quad (11)$$

where  $\mathbf{c}(t_0)$  is the location vector of the logical center of the group at  $t = t_0$ ,  $\vec{RP}$  is a vector from the logical center to the reference point, and  $\vec{RM}(t_0)$  is the random motion vector at  $t = t_0$ . Let  $\tau$  be the update interval of the random motion vector; then at  $t = t_0 + \tau$ ,

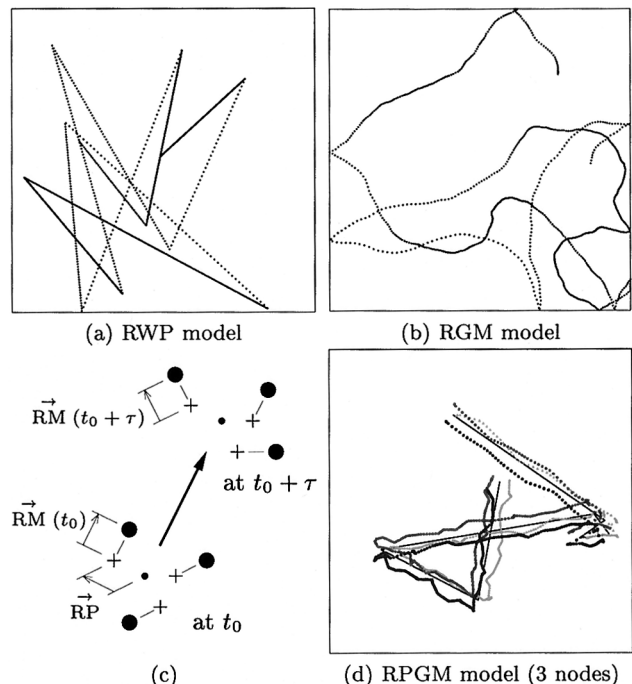
$$\mathbf{n}(t_0 + \tau) = \mathbf{c}(t_0 + \tau) + \vec{RP} + \vec{RM}(t_0 + \tau). \quad (12)$$

For  $t_0 \leq t \leq t_0 + \tau$ ,  $\mathbf{n}(t)$  is given by

$$\mathbf{n}(t) = \frac{(t_0 + \tau - t) \cdot \mathbf{n}(t_0) + (t - t_0) \cdot \mathbf{n}(t_0 + \tau)}{\tau}. \quad (13)$$

Figure 3(c) depicts the movement of the RPGM model for a group with three nodes.

Figures 3(a), (b), and (d) illustrate the typical traveling patterns of a mobile node(s) in the RWP, RGM, and RPGM models, respectively. The larger spacing between the dots means higher speed of the node. The RWP model has a higher spatial node distribution at the center of the network than near the



**Fig. 3** Typical traveling patterns of a mobile node(s) moving in (a) RWP model, (b) RGM model, and (d) RPGM model. (c) Description of RPGM model.

boundaries [11], while the RGM model has a relatively uniform spatial node distribution over the entire network. Moving at the same speed, RWP node will travel farther than RGM node for the same time duration due to the traveling pattern. Figure 3(d) illustrates a group of three nodes in the RPGM model with the logical center moving according to the RWP model. Also shown is the trajectory of the logical center of the group.

## 5. Network Scenarios

Three different types of network scenarios are used to evaluate the proposed mobility measure. The network scenarios are designed to represent a variety of networks with different motion characteristics to evaluate the consistency of the proposed mobility measure.

For convenience, all physical dimensions are normalized by the communication range  $R$ . Thus, “distance 2” means the distance of two times  $R$ . Similarly, “speed 0.5” means the traveling speed of  $0.5R$  per second. 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  $\theta$  are updated every  $\Delta t = 0.2$  seconds, where  $\Delta v_{\max} = 0.1$  and  $\Delta\theta_{\max} = 0.1\pi$ .

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



group are located at the logical center of the tour group.  $RM_{\max} = 0.5$  is used for the tour groups. Upon arrival at the next presentation group, a tour group stays for a random time duration in seconds of uniform distribution  $U[0, 10]$  before it moves to the next presentation group. After visiting the last presentation group, a tour group leaves the convention area. Because of the arrival and leaving of the tour groups, the number of nodes in the network is a random variable. See Table 1(c) for the summary of the mobility model parameters.

## 6. Simulation Results

For each network scenario, the normalized link change rate is compared with the mobility measures. Because  $M^G(t)$  and  $M^I(t)$  are mobility measures normalized by the number of nodes  $N$ , the link change rate is also normalized. To be specific, since there are  $N C_2 = N(N-1)/2$  node pairs in a network with  $N$  nodes, the link change rate is divided by  $N(N-1)/2$ . For all scenarios, 500 seconds of warm up time was used to let the network reach steady state before 500 seconds of simulations. Since it is assumed that the network is in steady state, the time averages of the mobility measures and the normalized link change rate are used in the comparison. As discussed below,  $M^G$  and the time average of the normalized link change rate show strong linear relationship for the entire network scenarios.

For the time average of the mobility measures,  $M^G$  and  $M^I$ , (6) is approximated by taking  $M^G(t)$  and  $M^I(t)$  every 0.01 seconds and averaging in time.

Unlike the mobility measure, link changes are events occurring at discrete times. To calculate the time average of the normalized link change rate, we define  $L(t)$  as the number of link changes occurred during the time interval  $[0, t]$ . Then

$$l(t) = \frac{dL(t)}{dt} = \sum_k \delta(t - t_k), \quad (14)$$

where  $t_k$  is the time instance of the  $k$ -th link change. The time average of the *normalized* link change rate is given by

$$\bar{l} = \frac{1}{T} \int_0^T \frac{l(t)}{\frac{N(t)(N(t)-1)}{2}} dt. \quad (15)$$

If  $N(t)$  is a constant  $N$ , (15) can be written as

$$\bar{l} = \frac{2}{N(N-1)} \frac{L(T)}{T}. \quad (16)$$

If  $N(t)$  is a function of time, then from (14) and (15)

$$\bar{l} = \frac{1}{T} \sum_{k=1}^{L(T)} \frac{2}{N(t_k)(N(t_k)-1)}. \quad (17)$$

To calculate the average normalized link change rate,

(16) is used for type 1 and 2 scenarios (S1, S2,  $\dots$ , S7, T1, T2,  $\dots$ , T5, and G1, G2,  $\dots$ , G5), and (17) is used for type 3 scenario (C1).

If the network is not in steady state, the normalized link change rate at time  $t$  is given by

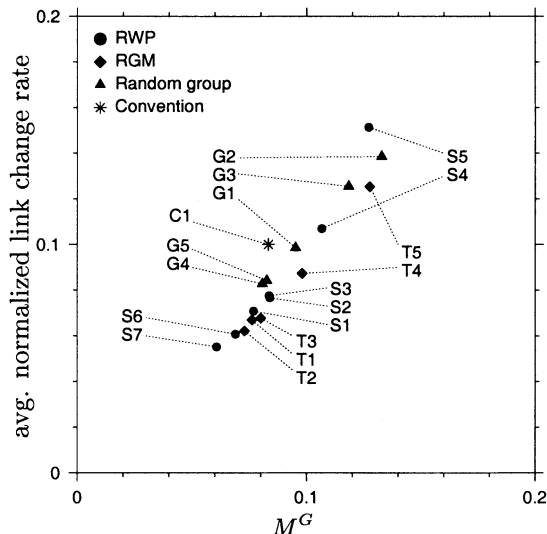
$$\bar{l}(t) = \frac{1}{2\Delta t} \int_{t-\Delta t}^{t+\Delta t} \frac{l(\tau)}{\frac{N(\tau)(N(\tau)-1)}{2}} d\tau \quad (18)$$

for some  $\Delta t$ . However, the choice of  $\Delta t$  can be quite tricky. If  $\Delta t$  is too large,  $\bar{l}(t)$  cannot represent the time dependence of the link change rate accurately. If  $\Delta t$  is too small,  $\bar{l}(t)$  can be a poor estimate of the link change rate.

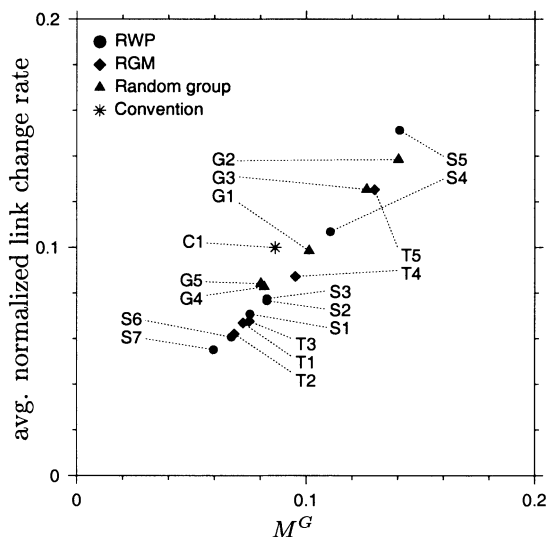
The simulation results show that  $M^G$  exhibits a consistent linear relationship with the average normalized link change rate for the entire network scenarios considered. On the other hand, though it is a considerable improvement over the existing mobility factor proposed in [9],  $M^I$  is affected by many factors in the network scenario such as the mobility model used and the physical dimension of the network, and displayed little linear relationship with the average normalized link change rate.

Figure 5(a) shows the simulation results for the mobility measure  $M^G$  with parameter  $r = 3$ . As shown in the figure, the average normalized link change rate  $\bar{l}$  show a strong linear relationship with  $M^G$  for the entire network scenarios of type 1, 2, and 3. Note that, for type 1 scenarios with RWP and RGM models, the linear relationship is well maintained for the changes in the number of nodes  $N$  (RWP: S1–S2–S3, RGM: T1–T2–T3), the physical dimension of the network (RWP: S2–S4–S5, RGM: T2–T4–T5), and the pause time (RWP: S2–S6–S7). In type 2 scenarios with RPGM model, while the groups of G1 and G2 have statically the same logical center movement, G2 has more intra-group node movement than G1 has. As a result, G2 results in larger link change rate and mobility measure  $M^G$  than G1 does. As expected, for scenario G3 where two different kinds of groups from G1 and G2 are mixed, the resulting  $M^G$  and  $\bar{l}$  are larger than for G1 but smaller than for G2. C1 represents the convention scenario. During the 500 second simulation time, on average there were 81.8 nodes, 16.1 tour groups in the convention area, and the average tour time for a group was 167.8 seconds. The result for scenario C1 also shows reasonable consistency with the results for other scenarios.

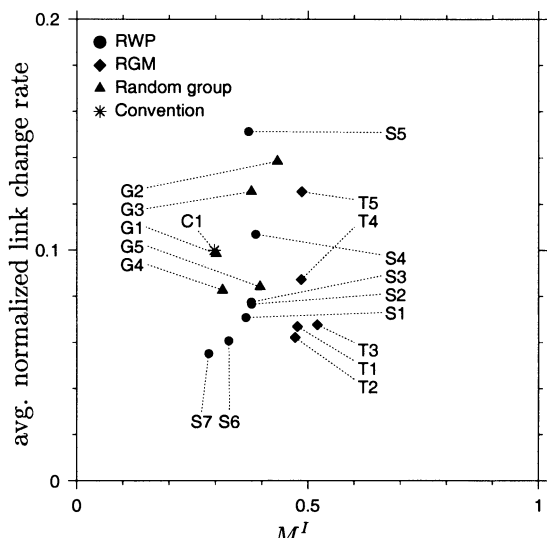
As discussed in Sect. 2, by using larger  $r$ , we can give more weight to the movements of the nodes near the communication range  $R$ . Figure 5(b) shows the simulation results for the mobility measure  $M^G$  with parameter  $r = 5$ . As shown in the figure, the relationship between  $\bar{l}$  and  $M^G$  is even more linear than it is observed in Fig. 5(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.



(a)  $M^G$  with  $r = 3$ .



(b)  $M^G$  with  $r = 5$ .



(c)  $M^I$ .

Fig. 5 Normalized link change rate vs. mobility measure.

As shown in Fig. 5(c), unlike the mobility measure  $M^G$ ,  $M^I$  exhibits little linear relationship with  $\bar{l}$ . For example, while  $M^I$  shows no significant changes for different physical dimensions of the network, the link change rate increases considerably as the physical dimension of the network decreases (RWP: S2–S4–S5, RGM: T2–F4–T5). Furthermore,  $M^I$  is affected by the choice of mobility model used. Comparing the scenarios with RWP model (S1–S5) with the scenarios with RGM model (T1–T5), we notice that scenarios with RGM model result in larger  $M^I$  but smaller link change rate than the corresponding scenarios with RWP model. This tendency of RGM model giving larger  $M^I$  is also observed between G4 and G5, where RGM model is mixed with RWP and RGM models respectively. This is due to the difference of the traveling pattern of a node in RWP and RGM models. The traveling pattern of a node in RWP model moves following a piecewise straight path, and thus travels farther than a node moving in RGM model traveling at the same speed for the same time period resulting in higher probability of link change. The lack of consistency of  $M^I$  can be attributed to the inability of  $M^I$  to regulate the effect of the atypical characteristics of each network scenario.

### 7. Conclusion

In this paper, we proposed a canonical mobility measure for MANETs. The consistency of the proposed mobility measure was demonstrated by the consistent linear relationship between the mobility measure and the link change rate for various simulation scenarios. The proposed mobility measure provides a unified means of measuring the degree of mobility in a MANET, offering researchers of MANET a reference with the help of which independent studies of network performance can be compared.

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