GPS-FREE MOBILITY METRICS FOR MOBILE AD-HOC NETWORKS

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ABSTRACT

Efficient mobility metrics are necessary for mobile ad-hoc networks to measure the impact of node mobility on performance. Normally, measuring mobility requires the use of complex localization systems. In this paper, we propose a new mobility metric, the *intra-vicinity dependency*, for performance measurements. Its main novelty is that it can fully capture the relative motions between a node and its vicinity in a 2D plane, in real-time, using simple triangulation. Variants of this metric are proposed for predicting the performance of networks that follow group and random mobility models (e.g. inter-group inter-meeting times and packet delivery rate). To make the proposed mobility metrics more robust in noisy environments, a calibration method is also proposed for improving accuracy. Experimental results show that, without the help of any localization systems, the proposed metrics enable a more accurate approximation of the average relative speed between mobile nodes/groups than existing methods. It is also shown that the proposed metrics yield excellent performance when they are used to predict the inter-group inter-meeting times for networks that follow the RPGM model and to estimate the packet delivery rate for those that follow the RWP model.

1 INTRODUCTION

A mobile ad-hoc network is a collection of mobile nodes that form infrastructureless temporary networks. Communications in mobile ad-hoc networks rely on distributed routing protocols which can cope with frequent changes in network topologies caused by nodal mobility. The performance of an ad-hoc routing protocol depends on its ability to adapt to the dynamics of the network and to work out the best strategy for packet delivery. Thus, it is important to have quantitative metrics that reflect the quality of communications based on node mobility and topological dynamics.

Common measures of nodal mobility and topological dynamics [1] [2] are derived from the relative velocities between pairs of mobile nodes. To obtain the relative velocity between a pair of nodes, knowledge of their locations or motion vectors (speed, direction, etc.) in real-time is necessary. Such knowledge can be inferred from changing positions of mobile nodes with the help of a localization system e.g. GPS [3] or GPS-free positioning systems [4] [5]. However, the GPS signal is normally too weak to be of any use indoors. The GPS receiver may also be impractical for some mobile devices due to size or power constraints. In addition, GPS-free positioning systems [4] [5] are too complex and computationally expensive just for measuring mobility. Some mobility metrics that do not require localization systems have been recently proposed. For example, in [6] the link duration is used as a mobility measure for adaptive protocols.

However, a problem of link duration is that its measurement cannot always be carried out in real-time as the links could exist for several minutes in low speed scenarios.

The mobility metric proposed in [7] does not need the assistance of localization systems either. It is based on the time derivative of the distance (or *distance change rate*) between pairs of neighbouring nodes. Kwak et al. [8] further extended this work to create a mobility measure that puts more weight on nodal movements closer to the communication range. These mobility metrics have been shown to have strong correlation with the link change rate of a network. However, the approach of measuring the inter-node mobility (the *distance change rate*) is not accurate enough as it can only reflect the relative motions in the direction of line of sight. The relative movements between nodes in the 2D space involve their relative motions in the horizontal and vertical scales. In fact, the *distance change rate* underestimates the network mobility. This problem limits the applications of the these metrics to only mapping functions (e.g. from the metrics to the link change rates) that does not require the exact quantity of the relative motion.

In this paper, we propose a new mobility metric, the *intra-vicinity dependency*, for measuring the performance of the network. The main novelty is that it can fully capture the relative motions between a node and its vicinity (e.g. its surrounding one-hop neighbours) in a 2D plane, in real-time, using distance estimates and simple triangulation. It can be used as a substitute for the average relative speed when the true speed information of mobile nodes is not available. Variants of this metric are proposed for predicting performance of networks that follow group and random mobility models (e.g. inter-group inter-meeting times[1] and packet delivery rate[2]). To make the proposed mobility metrics more robust in noisy environments, a calibration method is also proposed for improving accuracy. The performance of the metrics is validated by computer simulations covering various mobility models (e.g. the Random WayPoint model (RWP), Restricted Random Waypoint (R2WP), the City Section Mobility model (CSM), and the Reference Point Group Mobility (RPGM) model) [9] [10]. Experimental results show that, without the help of any localization systems, the proposed metrics enables a more accurate approximation of the average relative speed between mobile nodes/groups than the existing methods [7] [8]. It is also shown in the experiments that the proposed metrics yield excellent performance when they are used to predict the inter-group inter-meeting times for networks that follow the RPGM model [9] and to estimate the packet delivery rate for those that follow the RWP model [9].

2 THE GPS-FREE MOBILITY METRICS

In this section, we present the proposed mobility metric the *intra-vicinity dependency* and its variants (e.g. the *inter-group mobility* and the *intra-vicinity mobility*), as well as the associated measuring methods and algorithms.

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[1] Defined as the duration between the time when a group of nodes encounter the other group and the next time when they meet again

[2] Defined as the total number of packets received divided by the total number of packets transmitted

2.1 The Intra-Vicinity Dependency

As mobile nodes move around, the relative motions between a node and its one-hop neighbours cause their relative positions, and hence the network topology, to change in time. Thus, the impact of network mobility on the communication performance can be inferred from the change rates of inter-node relative positions. However, measuring the change rates of relative positions between nodes cannot be accomplished by simply taking the time derivative of the inter-node distances [7] [8]. As shown in Fig.1, the minimal deviations in the distance samples (e.g. d_i, d_{i+1}, d_{i+2}) measured at every Δt do not match the obvious relative movements between node *i* and *j*, i.e. $|d_{i+1} - d_i| \ll \mathcal{M}_j$.

To fully capture the relative motions between a node and its one-hop neighbours, we propose a mobility metric, *intra-vicinity dependency*. The measurement of this metric is based on knowledge of a mobile node's position relative to the other pairs of nodes in its neighbourhood. We assume that each node periodically measures the distances to its one-hop neighbours by means of received signal strength (RSSI), time-of-arrival (ToA) or time-difference-of-arrival (TDoA) measurements. Every node also reports its collection of distance estimates to all of its one-hop neighbours at a frequency of $1/\Delta t$. Thus, every node knows not only the distances to its one-hop neighbours but also those between neighbouring nodes within the vicinity. Let $\mathcal{R}_i$ be the set of one-hop neighbours of node *i* and $\mathcal{U}_i$ the set of pairs of *i*'s one-hop neighbours that are also one-hop away from each other. We have $\mathcal{U}_i = \{(j,k)|j \in \mathcal{R}_i \wedge k \in \mathcal{R}_i \wedge j \in \mathcal{R}_k \wedge k \in \mathcal{R}_j\}$, where (*j, k*) can be any combinations of node couples within node *i*'s vicinity that satisfy this condition. For each pair of nodes $(j,k) \in \mathcal{U}_i$, as shown in Fig. 2, we use the distance *l* from node *i* to the midpoint of the line between nodes *j* and *k* as well as the included angle θ to interpret the relative position between node *i* and node pair (*j, k*). Given the estimates of distances between these nodes (e.g. d_{ij}, d_{jk} and d_{ik}), the values of *l* and θ can be obtained by simple triangulation as following:

$$l = \sqrt{d_{ij}^2 + (\frac{d_{jk}}{2})^2 - d_{ij}d_{jk}cos\varphi_{ik}} \tag{1}$$

$$\theta = cos^{-1}\frac{l^2 + (\frac{d_{jk}}{2})^2 - d_{ik}^2}{ld_{jk}} \tag{2}$$

where φ_{ik} is the included angle of d_{ij} and d_{jk} given by:

$$\varphi_{ik} = cos^{-1}\frac{d_{ij}^2 + d_{jk}^2 - d_{ik}^2}{2d_{ij}d_{jk}} \tag{3}$$

As node *i* moves, its position relative to node pair (*j, k*) would change in time. For example, as shown in Fig. 2, its position moves from (*l*, θ) at time $t - \Delta t$ to ($l^{'}$, $\theta^{'}$) at time *t*. Let $b = lcos\theta$, $a = lsin\theta$, $b^{'} = l^{'}cos\theta^{'}$ and $a^{'} = l^{'}sin\theta^{'}$ be node *i*'s position relative to node pair (*j, k*) in the horizontal and vertical scales at time $t - \Delta t$ and *t*, respectively. We have node *i*'s movement relative to node pair (*j, k*) over Δt as follows:

$$\mathcal{M}_{jk}^i(t - \Delta t, t) = \sqrt{(b' - b)^2 + (a' - a)^2} \tag{4}$$

We define the *intra-vicinity dependency* $\mathcal{MV}_i$ as a measure of the average relative movements between a mobile node *i* and the pairs of nodes in its one-hop vicinity. $\mathcal{MV}_i$ could be measured at every time slot Δt by:

$$\mathcal{MV}_i(t - \Delta t, t) = \frac{1}{|\mathcal{U}_i|} \sum_{j,k \in \mathcal{U}_i} \frac{\mathcal{M}^i_{jk}(t - \Delta t, t)}{\Delta t} \tag{5}$$

where $|\mathcal{U}_i|$is the cardinality of the set $\mathcal{U}_i$.

2.2 The Inter-Group Mobility

When the movements of mobile nodes follow group mobility models (e.g. RPGM), the connections between nodes in the same mobility group is relatively stable and topological changes are mainly due to the relative movements between mobility groups. Therefore, it is necessary to define a mobility metric for the inter-group relative motions. We define the *inter-group mobility* $\mathcal{MG}_i$ as a metric of the average relative moving speed between node *i*'s mobility group and the neighbouring groups. In Fig.2, if node *i* belongs to one mobility group and node pair (*j*, *k*) belongs to another, Eq.4 can be a good approximation of the relative movement between these two groups. Let $\mathcal{U}^G_i$ be the set of node pairs that are one-hop away from node *i* but are not belonging to *i*'s mobility group, we have $\mathcal{U}^G_i \subseteq \mathcal{U}_i$. $\mathcal{MG}_i$ can be given at every Δt by:

$$\mathcal{MG}_i(t - \Delta t, t) = \frac{1}{|\mathcal{U}^G_i|} \sum_{j,k \in \mathcal{U}^G_i} \frac{\mathcal{M}^i_{jk}(t - \Delta t, t)}{\Delta t} \tag{6}$$

where $|\mathcal{U}^G_i|$is the cardinality of the set $\mathcal{U}^G_i$, which can be obtained by deploying the Sequential Clustering (SC) algorithm [11] to classify node i's movements relative to its vicinity, i.e. $\{\mathcal{M}^i_{jk}(t - \Delta t, t), j, k \in \mathcal{U}_i\}$.

2.3 The Intra-Vicinity Mobility

The *intra-vicinity mobility* is proposed to capture the impact of nodal mobility on the network connectivity. The *intra-vicinity dependency* is a reflection of the amount of inter-node relative movements for networks following random mobility models (e.g. RWP). However, the network connectivity is not determined by the *intra-vicinity dependency* alone. The impact of the inter-node relative movements on the network connectivity depends on the radio radius, *r*, i.e. the longer the radio radius the less the impact of the relative mobility on the network connectivity and vice versa. We define the *intra-vicinity mobility* $\mathcal{MR}_i$ as a metric of the average relative movements between a mobile node *i* and the node pairs in its one-hop vicinity within the radio range *r*. The value of $\mathcal{MR}_i$ over time Δt can be simply derived from Eq.5 as follows:

$$\mathcal{MR}_i(t - \Delta t, t) = \frac{\mathcal{MV}_i(t - \Delta t, t)}{r} \tag{7}$$

3 SIMULATION AND EVALUATION

In this section, we deploy the ns-2 simulator to simulate various network scenarios covering a wide range of nodal mobility. We evaluate the performance of the proposed mobility metrics in these scenarios and present the experimental results collected from the simulations.

3.1 The Simulation Model

The simulated mobile ad-hoc network consists of $\mathcal{N} = 40$ nodes moving around in a square area with the size of $\mathcal{L} \times \mathcal{L}$. Using both of the mobility modelling tools described in [10] and [12], the simulations cover a variety of scenarios and mobility models (e.g. the Random Waypoint model (RWP), the Restricted Random Waypoint (R2WP), the City Section Mobility model (CSM) and the Reference Point Group Mobility (RPGM) model).

The Restricted RWP mobility [10] was originally introduced to model the movement of mobiles within/between towns distributed in a large area. In this paper, we deploy R2WP to model the nodal mobility of a indoor scenario (e.g. a shopping mall with 3 large shops/rooms), in which mobiles have higher probability to perform restricted random movements in one of the 3 rooms and less chance to move between rooms. The CSM model (or the Manhattan Grid model in [12]) try to model nodal mobility in the street network of a metropolitan city. Using this model, we let mobiles move in the predefined streets that are separated by 12 building blocks and have a possibility of 0.6 to perform 90-degree turns at intersections. In the RPGM model, the 40 nodes are divided into 4 mobility groups (10 nodes per group). The motion of a group is defined by its logical centre, which moves according to the RWP model. The movement of an individual node is specified by the combination of the group motion and a random motion vector $\overrightarrow{\mathbf{RM}}$ [9]. In this experiment, the length and the direction of $\overrightarrow{\mathbf{RM}}$ have uniform distributions over [0, 120m] and [0, 2π), respectively.

For these mobility models, the pause probability of each node (group) is kept at 0 to produce continuous nodal (group) movements. The movement speed of a mobile node is uniformly distributed over [v_{min}, v_{max}], where v_{min} is fixed at 2.5m/s and v_{max} is varied from 5m/s to 40m/s to create different mobility scenarios.

The inter-node distances and mobility metrics are measured at intervals of $\Delta t = 1$ second for a duration of 300 seconds starting 1250 seconds after initialization. In the figures generated from the simulations, each data point corresponds to a mean of 30 repeated experiments with different random seeds.

3.2 The Experiments and Results

We performed four sets of experiments to evaluate the performance of the proposed mobility metrics and to demonstrate their applications in various scenarios.

3.2.1 Experiment 1: The first experiment is to evaluate the performance of the *intra-vicinity dependency* and the *inter-group mobility* as a substitute for the average inter-node relative speed for networks following the RWP, R2WP and

CSM models and the inter-group relative speed for those following the RPGM model, respectively. In this experiment, r is fixed at 150m while $\mathcal{L}$ is set as 800m.

Fig.3 gives a comparison between $\mathcal{MV}$ (the network and time mean of $\mathcal{MV}_i$) and the mean inter-node *distance change rate*[3] [7] [8] regarding their similarity to the average inter-node relative speed calculated from the location information[4] of mobile nodes moving in the RWP model. As shown in Fig.3, with an average deviation less than 1.5m/s the mean *intra-vicinity dependency* $\mathcal{MV}$ is a good estimate of the average inter-node relative speed over the wide range of maximum speed limits. On the contrary, as it only captures the relative motion in the direction of line of sight, the *distance change rate* underestimates the average inter-group relative speed especially with high speed limits.

Fig.4 presents the results of the same comparison between $\mathcal{MV}$ and the mean *distance change rate* for the R2WP model. As shown in Fig.4, the performance of $\mathcal{MV}$ is still promising. The average deviation between $\mathcal{MV}$ and the measured mean relative speed is merely 0.7m/s. Compared to Fig.3, the gap between the *distance change rate* and the measured relative speed appears to be smaller. This may be due to that nodal mobility in the R2WP model are less-random. As their orientations are often restricted by the shape of the rooms.

In Fig.5, we have also made a similar comparison between $\mathcal{MV}$ and the mean inter-node *distance change rate* for networks moving in the CSM model. Fig.5 shows that, in the CSM model, $\mathcal{MV}$ generally has a good match with the average inter-node relative speed, except that at the speed limit of 35m/s or higher $\mathcal{MV}$ is as inaccurate as the *distance change rate*. This is due to the negative effects of more 90-degree turns from cars arriving at intersections. Fig.5 also shows that the *distance change rate* has a better accuracy in approximating the average inter-node relative speed in the CSM model than in the RWP and the R2WP model (see Fig.3 and Fig.4). The reason is because that in the CSM model most of the relative movements between mobiles are one-dimensional in the network of streets hence they can be well captured by the *distance change rate*.

Fig.6 compares $\mathcal{MG}$ (the network and time average of $\mathcal{MG}_i$) from the mean *distance change rate* for being a substitute for the actual inter-group relative speed obtained from the nodal location information. As shown in Fig.6, with an average deviation less than 1m/s $\mathcal{MG}$ is an accurate approximation of the inter-group relative speed regardless of the speed limits. The *distance change rate* is shown to have underestimated the inter-group relative speed due to the aforementioned reason.

3.2.2 Experiment 2:

In the second experiment, we examined the performance of the *intra-vicinity dependency* and the *inter-group mobility* with noisy range information. Without taking the effect of Non-Line-of-Sight (NLOS) into account, a distance estimate (e.g. measured using TDoA) from a noisy environment at time *t* (denoted as $\hat{d}_t$) can be simply modelled as:

$$\hat{d}_t = d_t + \epsilon_t \tag{8}$$

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[3] Given the time varying distance estimate between node *i* and *j*, $d_{ij}(t)$, the distance change rate between i and j is given by: $\frac{d}{dt}d_{ij}(t)$

[4] Let $(\mathcal{V}_x^i, \mathcal{V}_y^i)$ and $(\mathcal{V}_x^j, \mathcal{V}_y^j)$ be node *i* and *j*'s motion vector, respectively. The relative speed between *i* and *j* can be calculated by: $\sqrt{(\mathcal{V}_x^i - \mathcal{V}_x^j)^2 + (\mathcal{V}_y^i - \mathcal{V}_y^j)^2}$

where d_t is the true distance and ϵ_t is the measurement noise that can be modelled as a zero-mean Gaussian random variable with variance σ_ϵ^2. In the experiment, σ_ϵ ranges between 0m to 4m, which is achievable with off-the-shelf products [13]. We evaluated the normalized bias between $\mathcal{MV}$, the mean *intra-vicinity dependency*, and the true average inter-node relative speed, as well as that between $\mathcal{MG}$, the mean *inter-group mobility*, and the actual average relative speed between neighbouring mobility groups. The normalized bias of $\mathcal{MV}$, denoted as $\sigma_{\mathcal{MV}}$, is expressed as:

$$\sigma_{\mathcal{MV}} = \frac{\mathcal{MV}}{\bar{v}} - 1 \tag{9}$$

where $\bar{v}$ is the true average inter-node relative speed. The normalized bias of $\mathcal{MG}$ can be expressed in a similar way as the form of Eq.9.

The normalized bias of the *intra-vicinity dependency* for the RWP, R2WP and the CSM model against increasing speed limits are shown in Fig.7(a), Fig.7(b) and Fig.7(c), respectively. The normalized bias of the *inter-group mobility* for the RPGM model is shown in Fig.7(d). We can observe from Fig.7 that in noisy conditions the mobility metrics overestimate the real network mobility with normalized bias that are increasing with the noise variance σ_ϵ^2 regardless of the mobility models. However, the normalized bias of $\mathcal{MV}$ and $\mathcal{MG}$ are inversely proportional to the nodal speed. This is due to the fact that estimation errors are mostly caused by the environmental noise and their values keep stable while the nodal speed is being increased. Fig.7 indicates that a *calibration factor* can be derived from estimated distance errors (e.g. provided by the method reported in [14]) and average inter-node relative speed (e.g. using $\mathcal{MV}$ or $\mathcal{MG}$ as a substitute).

Fig.8 is a plot of the estimation errors (e.g. $|\mathcal{MV} - \bar{v}|$) for the R2WP model against various combinations of inter-node relative speeds (measured by $\mathcal{MV}$) and noise levels (estimated as σ_ϵ). We have also made a 3^{rd} order polynomial surface fitting for the data in Fig.8 to predict estimation errors based on nodal speed and noise variance. The fitted surface has a goodness (R-square) value of 0.994. The fitting function, $\mathcal{F}^c(\mathcal{MV}, \sigma_\epsilon)$, is as follows:

$$\begin{aligned}\mathcal{F}^c(\mathcal{MV}, \sigma_\epsilon) = {} & 1.5132 + 1.2799\mathcal{MV} - 0.3563\sigma_\epsilon + 0.6004\mathcal{MV}^2 + 0.0496\sigma_\epsilon^2 - 0.1893\mathcal{MV}\sigma_\epsilon \\ & -0.0127\mathcal{MV}^3 - 0.0018\sigma_\epsilon^3 + 0.0055\mathcal{MV}\sigma_\epsilon^2 - 0.0184\mathcal{MV}^2\sigma_\epsilon \qquad (\mathcal{MV}{>}0,\ \sigma_\epsilon{>}0)\end{aligned} \tag{10}$$

The function $\mathcal{F}^c(\mathcal{MV}, \sigma_\epsilon)$ can be used to produce a calibration factor to reduce the estimation errors caused by inaccurate distance information. Therefore we can use a calibrated *intra-vicinity dependency*, $\mathcal{MV} - \mathcal{F}^c(\mathcal{MV}, \sigma_\epsilon)$, for noisy environments. The near-perfect normalized bias of the calibrated $\mathcal{MV}$ presented in Fig.9 proves that the method is effective for the R2WP model. Calibration factors for other mobility models can be derived with a same function using different parameters. As the mobility models have different levels of sensitivity to noisy distance estimates due to their distinct nodal movement patterns.

3.2.3 Experiment3: The third experiment is to demonstrate the application of the *inter-group mobility* for estimating the inter-group inter-meeting times for networks following the RPGM model. The simulation settings of this experiment are similar to those of the first experiment, except that the simulation period after initiation is extended to 1500 seconds for collecting the actual inter-group inter-meeting times. In the RPGM model, the logical centre of each mobility group is actually moving according to the RWP model. Therefore, we can predict the mean inter-meeting times between mobility groups $\mathcal{T}^G$ using Eq.11 [15, p. 93].

$$\mathcal{T}^G = \frac{\mathcal{L}^2}{2\omega r^G \bar{\mathcal{V}}} \tag{11}$$

where $\omega \approx 1.3683$ is a specific constant for the RWP model, $\bar{\mathcal{V}}$ is the mean inter-group relative speed and r^G is the combined radio range of a mobility group. We have $r^G \geq r$ and $r^G \rightarrow r$ when $r \gg |\overrightarrow{RM}|$. We used the value of r to approximate r^G for simplicity. Assuming the speed information of mobile nodes is not available, we tried to substitute $\bar{\mathcal{V}}$ with $\mathcal{MG}$ or the mean *distance change rate*.

Fig.10 compares the performance of estimating the mean inter-group inter-meeting times using $\mathcal{MG}$ (the average *inter-group mobility*) and the average *distance change rate* as substitutes for the true average inter-group relative speed. As demonstrated in Fig.10, using $\mathcal{MG}$ for $\bar{\mathcal{V}}$ in Eq.11 the predicted group inter-meeting times is very close to those that are measured using simulation. The use of the *distance change rate* approach leads to an overestimation of $\mathcal{MG}$ due to the fact that the *distance change rate* is an underestimation of the average inter-group relative speed $\bar{\mathcal{V}}$. When the network mobility is low, such an overestimation can be more than 200 seconds.

3.2.4 Experiment 4: The fourth experiment is to investigate the performance of using the *intra-vicinity mobility* as a metric of the packet delivery rate. In this experiment, we randomly choose 3 UDP data source/sink pairs from a network following the RWP mobility model to generate a total of 50 packets per second of Constant Bit Rate (CBR) traffic in the network. More source/sink pairs were also tested. But in these cases more packets are lost due to congestion, which makes it difficult to distinguish the impact of mobility from that of congestion. The radio radius r is varied from 100m to 250m (with a step of 50m) and the side length of the simulation area $\mathcal{L}$ from 400m to 1000m (with a step of 200m) to create 4 sets of network scenarios with a constant node density.

Fig.11 gives a plot of the CBR data packets delivery rate as the mean *intra-vicinity mobility* $\mathcal{MR}$ increases. From Fig.11 we see a strong relationship between the packet delivery rate and $\mathcal{MR}$, for which a 3^{rd} order polynomial curve fitting function is derived (Eq.12). The goodness of the fitting is 0.985. The function $\mathcal{F}^r(\mathcal{MR})$ can be used by adaptive protocols to estimate the performance of packet delivery with varying network mobility.

$$\begin{aligned} \mathcal{F}^r(\mathcal{MR}) &= -108.1\mathcal{MR}^3 + 39.14\mathcal{MR}^2 \\ &\quad -6.627\mathcal{MR} + 0.9224 \qquad (\mathcal{MR}>0) \end{aligned} \tag{12}$$

4 CONCLUSION

In this paper, we propose a new GPS-free mobility metric, the *intra-vicinity dependency*, for measuring the performance of mobile ad-hoc networks. This metric can fully capture the relative motions between a mobile node and its vicinity in a 2D plane, in real-time, using simple triangulation. Variants of this metric are also proposed for predicting the performance of networks that follow group and random mobility models (e.g. inter-group inter-meeting times and packet delivery rate). To deal with estimation errors introduced by noisy distance estimates, a calibration method is also proposed for improving the accuracy of the mobility metrics. The reliability and accuracy of these metrics make them useful for ad-hoc routing protocols to adapt packet delivery for topological dynamics. We validate the performance of the metrics using ns-2 based simulations with several mobility models (e.g. RWP, R2WP, CSM, and RPGM). Experimental results show that, without the help of any location/speed information of mobile nodes, the proposed metrics enable a more accurate approximation of the average inter-node/inter-group relative speed than the existing method. It is also shown in the experiments that the proposed metrics yield excellent performance when they are used to predict the inter-group inter-meeting times for networks that follow the RPGM model and to estimate the packet delivery rate for those that follow the RWP model. Future work would involve some intelligent algorithms to determine the characteristics of the nodal movement pattern to enable adaptive estimations of calibration factors.

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LIST OF FIGURES

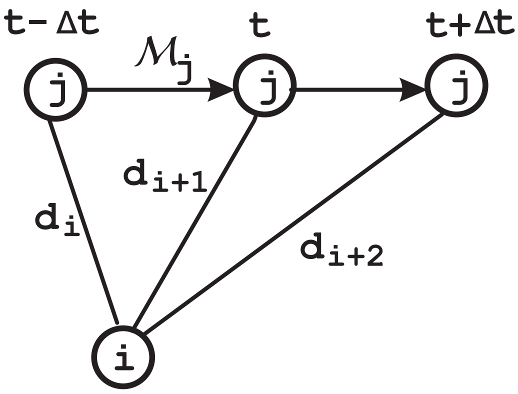


Fig. 1: The relative movements and distances between two mobile nodes *i* and *j*

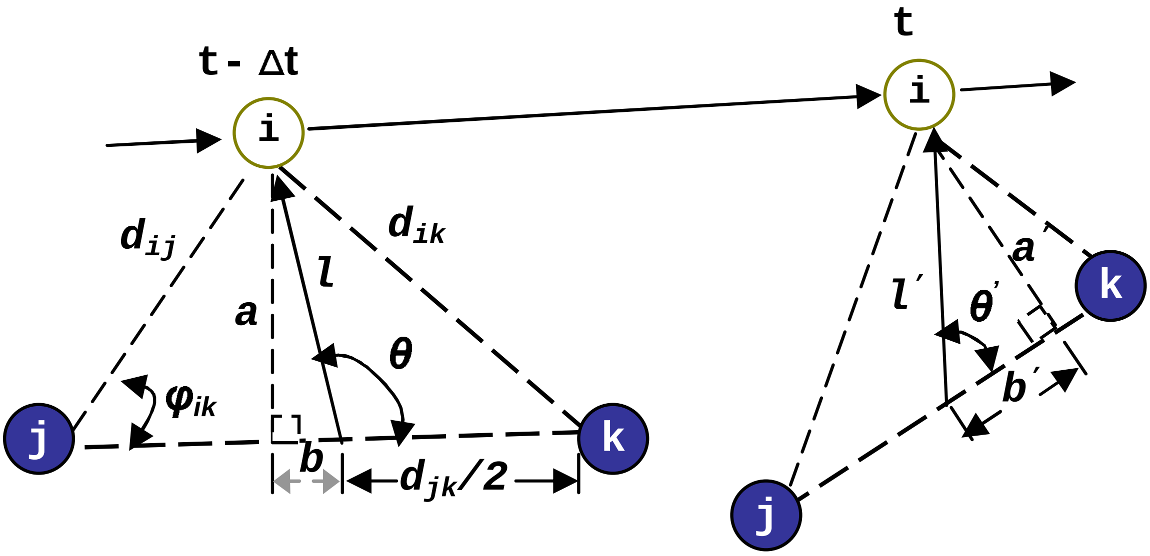


Fig. 2: The measurement of the relative movement between node i and its neighbouring node pair (j, k) over time slot Δt

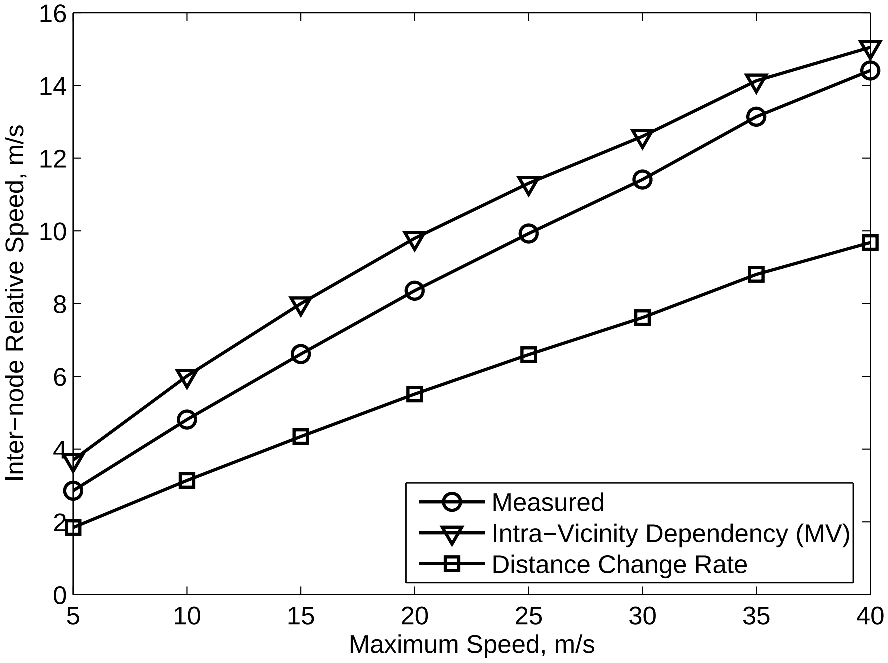


Fig. 3: Comparisons between the Intra-Vicinity Dependency and the Distance Change Rate as a substitute for the actual average inter-node relative speed for the RWP model

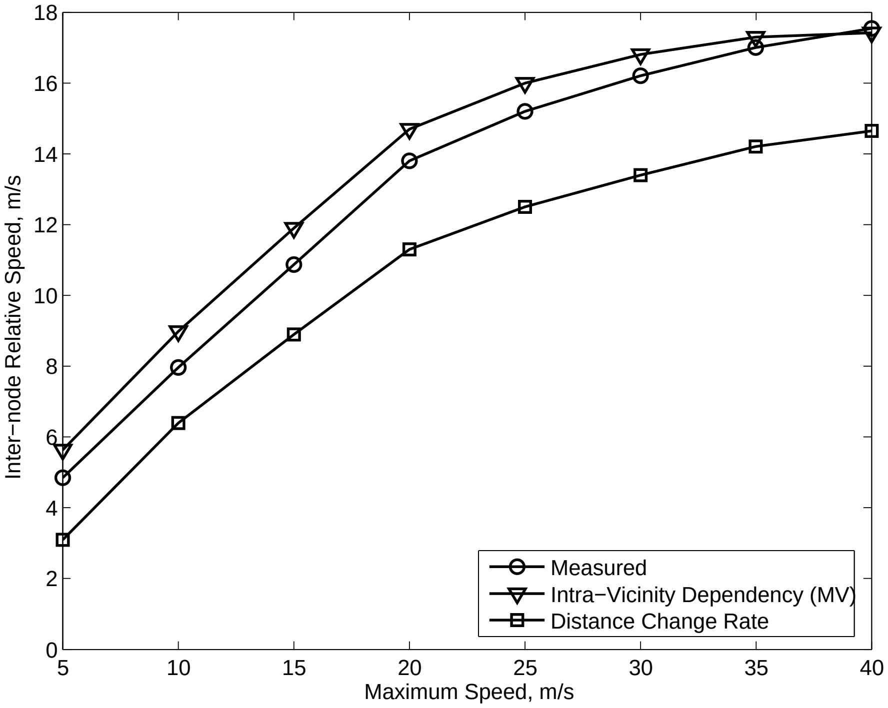


Fig. 4: Comparisons between the Intra-Vicinity Dependency and the Distance Change Rate as a substitute for the actual average inter-node relative speed for the R2WP model

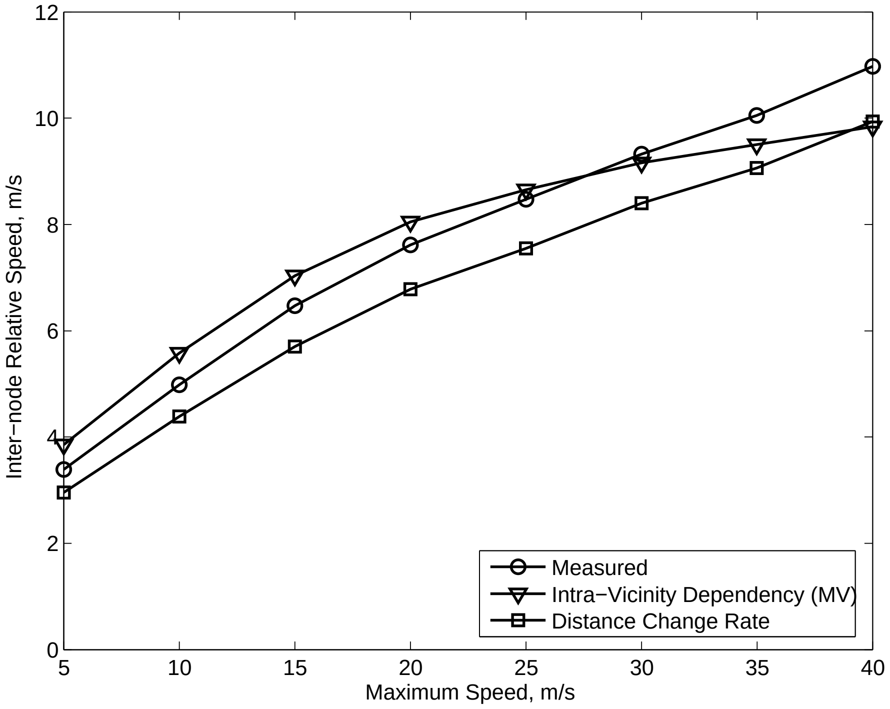


Fig. 5: Comparisons between the Intra-Vicinity Dependency and the Distance Change Rate as a substitute for the actual average inter-node relative speed for the CSM model

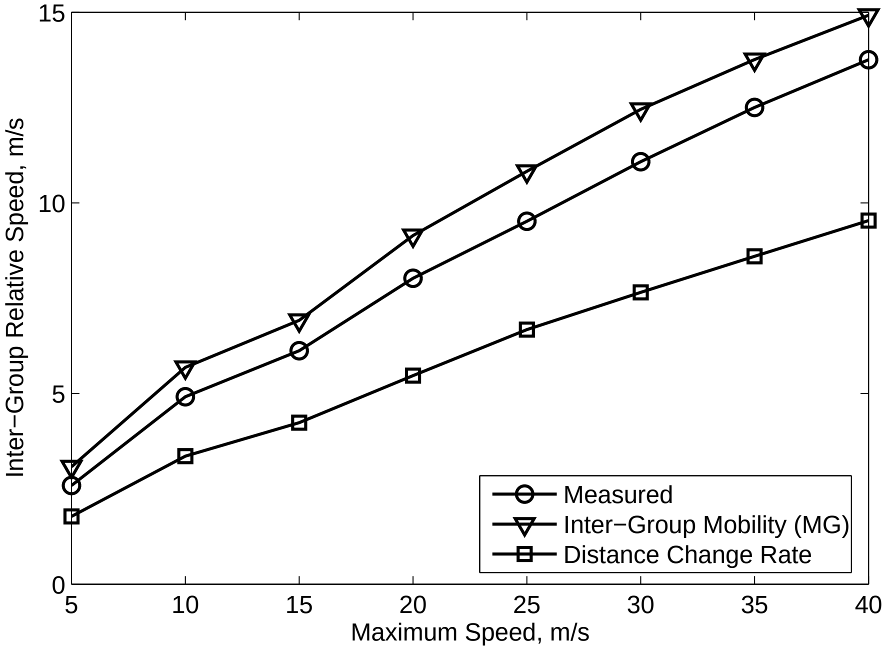
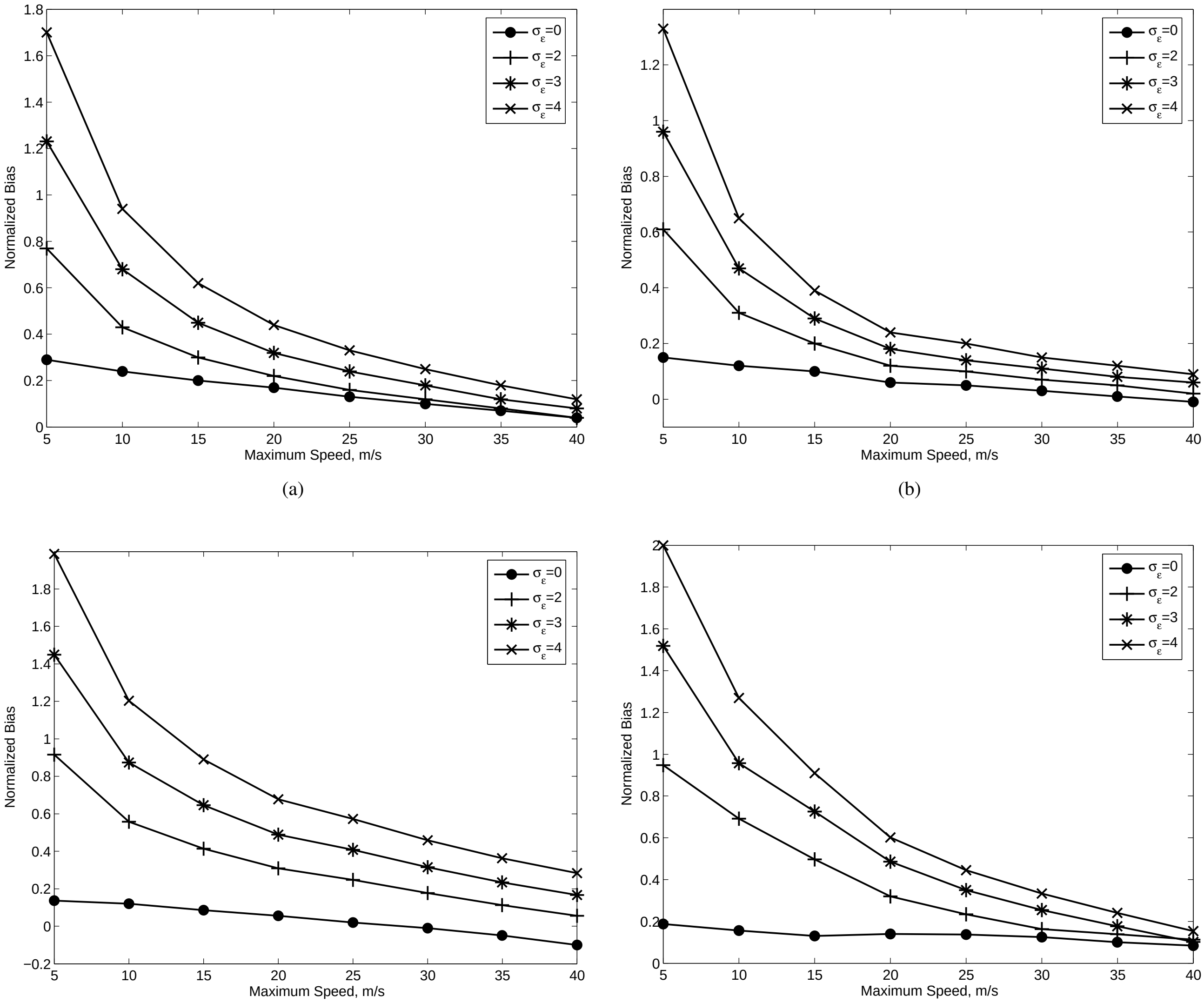


Fig. 6: Comparisons between the Inter-Group Mobility and the Distance Change Rate as a substitute for the actual average inter-group relative speed for the RPGM model



(a)

(b)

(c)

(d)

Fig. 7: the Normalized Bias of the mobility metrics. (a) Intra-Vicinity Dependency, RWP model, (b) Intra-Vicinity Dependency, R2WP model, (c) Intra-Vicinity Dependency, CSM model, (d) Inter-Group Mobility, RPGM model

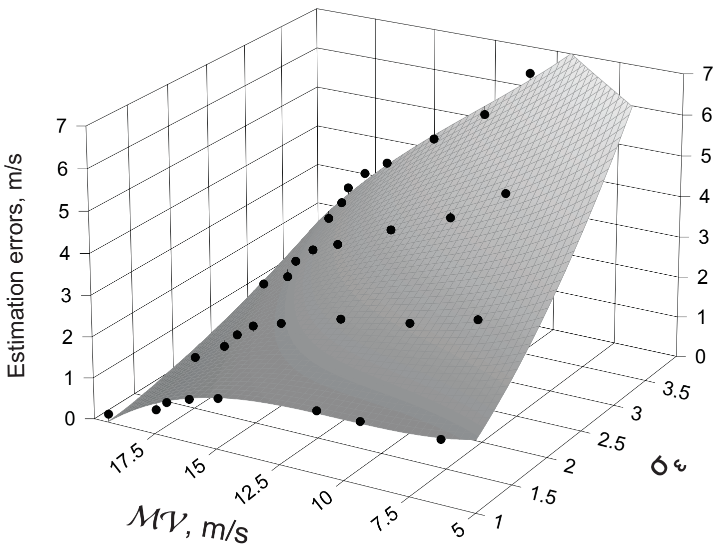


Fig. 8: Estimation errors vs. the Intra-Vicinity Dependency and noise variance, R2WP model

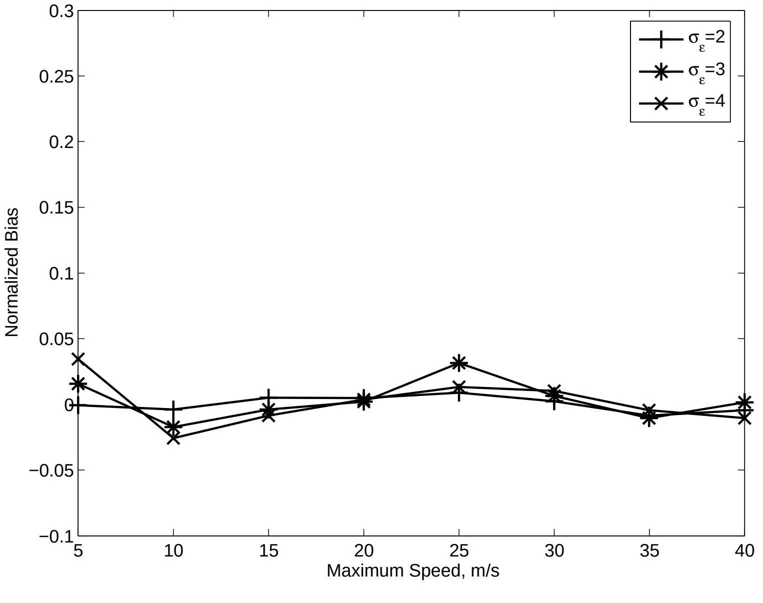


Fig. 9: the Normalized Bias of the calibrated Inter-Vicinity Dependency, R2WP model

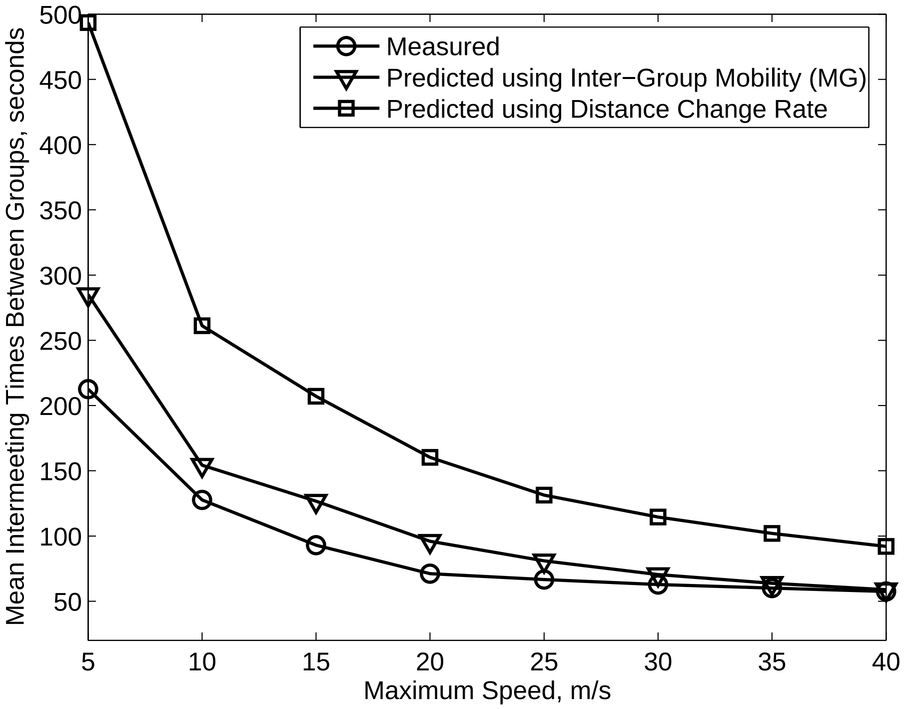


Fig. 10: Intermeeting Times Between Groups vs. Maximum Speed Limit

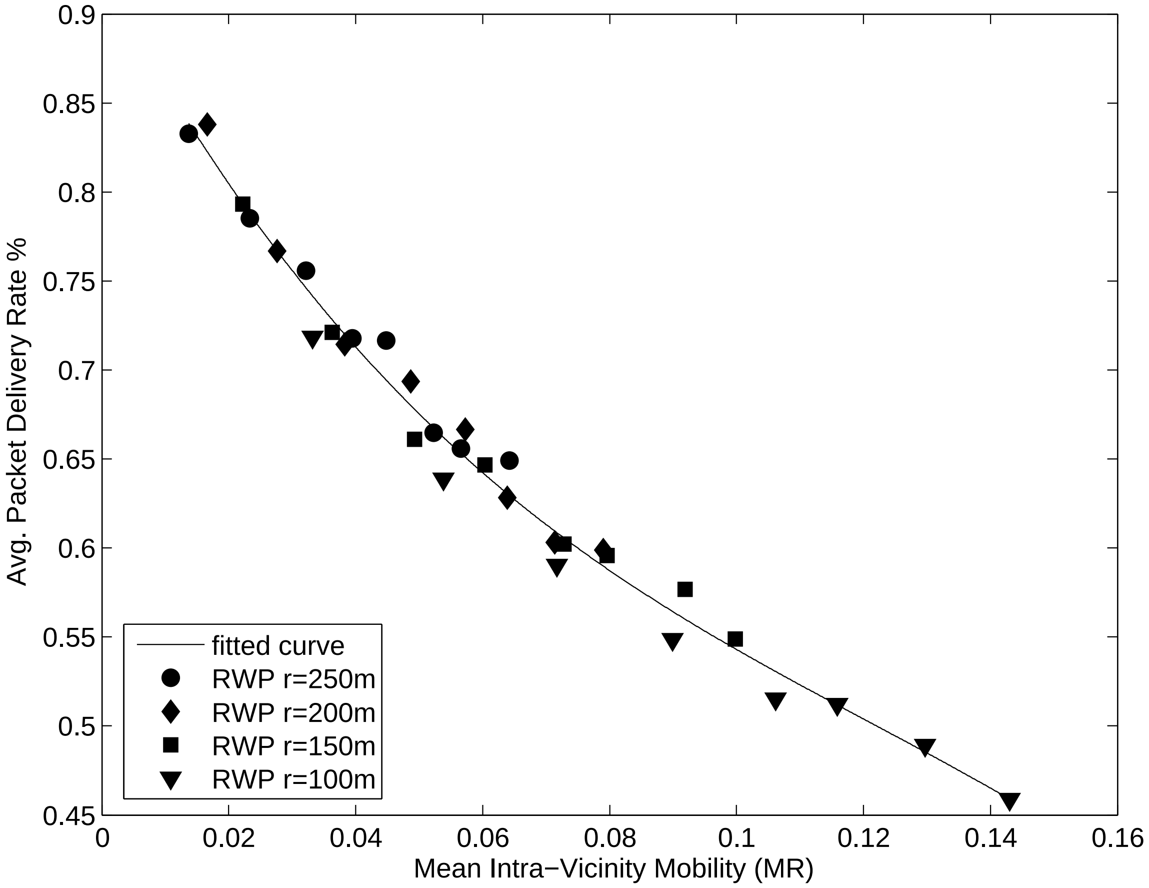


Fig. 11: Average Packet Delivery Rate vs. Mean *Intra-Vicinity Mobility*