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Abstract: The inter contact time (ICT) between two mobile nodes is essential for Delay Tolerant Networks (DTNs). The statistical characteristics of ICT significantly influence forwarding algorithms and end-to-end delay. Thus, a universal approach that could yield high accuracy should be adopted in obtaining the ICT distribution of node pairs. Some existing models depict the statistical characteristics of ICT; however, these models have detailed motion characteristics and lack general applicability in various mobility models and traces. In this paper, we propose a reliability mathematical model, called ICT Distribution-based Contact Model (IDCM), to demonstrate that the ICT between two mobile nodes is exponentially distributed and to verify that the exponential parameter of node pairs only relates to the historical contact numbers and cumulative ICTs. Through extensive experimental simulations and evaluations, we determined that IDCM not only characterizes contacts of node pairs accurately but also exhibits good performance in message delay analysis. Consequently, IDCM can provide guidelines on forwarding algorithm optimization, new protocol design and further network performance analysis.

Suggested Reviewers:

Dear Editor,

We would like to submit the enclosed manuscript entitled "IDCM: A General Inter Contact Time Distribution-based Contact Model for Delay Tolerant Networks", which we wish to be considered for publication in Computer Communications.

IDCM is inspired by our previous work "On the Distribution of Inter Contact Time for DTNs", which mainly focuses on the theoretical demonstration of ICT distribution of node pairs.

The citation is

[1] Hu, Yuting; Wang, Haiquan; Xia, Chunhe; Li Weiguo; Yang Ying, "On the Distribution of Inter Contact Time for DTNs", Local Computer Networks (LCN), 2012 IEEE 37th Conference on , vol., no., pp.152-155, 22-25 Oct. 2012.

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In IDCM, improvements are made not only in theoretical reasoning, but also in simulation and evaluation experiments in which IDCM exhibits superior universality and accuracy.

Copy of the Abatract: *The inter contact time (ICT) between two mobile nodes is essential for Delay Tolerant Networks (DTNs). The statistical characteristics of ICT significantly influence forwarding algorithms and end-to-end delay. Thus, a universal approach that could yield high accuracy should be adopted in obtaining the ICT distribution of node pairs. Some existing models depict the statistical characteristics of ICT; however, these models have detailed motion characteristics and lack general applicability in various mobility models and traces. In this paper, we propose a reliability mathematical model, called ICT Distribution-based Contact Model (IDCM), to demonstrate that the ICT between two mobile nodes is exponentially distributed and to verify that the exponential parameter of node pairs only relates to the historical contact numbers and cumulative ICTs. Through extensive experimental simulations and evaluations, we determined that IDCM not only characterizes contacts of node pairs accurately but also exhibits good performance in message delay analysis. Consequently, IDCM can provide guidelines on forwarding algorithm optimization, new protocol design and further network performance analysis.*

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IDCM: A General Inter Contact Time Distribution-based Contact Model for Delay Tolerant Networks

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Abstract
The inter contact time (ICT) between two mobile nodes is essential for Delay Tolerant Networks (DTNs). The statistical characteristics of ICT significantly influence forwarding algorithms and end-to-end delay. Thus, a universal approach that could yield high accuracy should be adopted in obtaining the ICT distribution of node pairs. Some existing models depict the statistical characteristics of ICT; however, these models have detailed motion characteristics and lack general applicability in various mobility models and traces. In this paper, we propose a reliability mathematical model, called ICT Distribution-based Contact Model (IDCM), to demonstrate that the ICT between two mobile nodes is exponentially distributed and to verify that the exponential parameter of node pairs only relates to the historical contact numbers and cumulative ICTs. Through extensive experimental simulations and evaluations, we determined that IDCM not only characterizes contacts of node pairs accurately but also exhibits good performance in message delay analysis. Consequently, IDCM can provide guidelines on forwarding algorithm optimization, new protocol design and further network performance analysis.

Keywords Delay Tolerant Networks (DTNs), Inter Contact Time (ICT), exponential distribution, parameter estimation, reliability mathematics

1 Introduction

Delay Tolerant Networks (DTNs) are message oriented reliable overlay network architecture with limited end-to-end connectivity and node resources. The high delay and intermittent connectivity of transmission opportunities among mobile nodes allows the routing of DTN to exploit a store-carry-forward mechanism [1, 4] that depends strongly on the frequency and duration of such encounters [6]. Inter contact time (ICT) [1, 3], which refers to the time taken by a mobile node to encounter another mobile node before forwarding messages, is an important metric of motion characteristics as well as a major component of end-to-end delay. Therefore, establishing a model that depicts the statistical characteristics of ICT is essential for improved contact prediction, new protocol design and network performance analysis for DTNs.

Considerable efforts have been made in designing models that can characterize ICT in DTNs. Most studies have focused on theoretical mobility models, such as Random Walk (RW) mobility model [7], Random Waypoint (RWP) mobility model [4, 5] and Random Direction (RD) mobility model [4, 5, 8]. Recently, real world mobility traces have also been used in ICT distribution studies [6, 11]. Majority of the studies have determined that the ICT between two mobile nodes generates exponential distribution and that the exponential parameters of ICTs relate to their motion characteristics [3, 4, 5, 8]. However, some existing models on the ICT distribution of node pairs concern too many detailed motion characteristics. Therefore, these models lack general applicability in various mobility models and real world traces. Although models that can generally provide concise ICT distribution via aggregate ICT statistics [6, 11], the accuracy of these models still needs to be improved for new protocol design and for further network performance analysis. The historical contact information of a node pair, which is a significant factor in ICT distribution, is also usually neglected.

Life testing in reliability theory offers solutions for obtaining ICT distribution by using historical contact information. This paper is inspired by life testing in reliability theory and by our previous work [9, 10], in which we proposed an approach certifying the exponential distribution of ICT between two mobile nodes. The current paper proposes a reliability mathematical model called ICT Distribution-based Contact Model (IDCM) to demonstrate that the exponential parameter of ICT between two mobile nodes only relates to the historical contact numbers and cumulative ICTs of the nodes. IDCM exhibits general applicability in providing ICT distribution of good accuracy and conciseness, which can be extremely valuable for forwarding algorithm optimization, new protocol design and further network performance analysis.

The remainder of this paper is organized as follows. After presenting the related work in Section 2, we provide basic notations and assumptions for IDCM in Section 3. In Section 4, the details of IDCM as demonstrated on the ICT distribution, as well as the analysis of the distribution parameter on the basis of point estimation and interval estimation, are provided. Simulations and evaluations will be presented in parameter settings, procedures and experimental results in Section 5. Finally, we conclude this paper in Section 6.

2 Related Works

Over the past few years, a number of studies have been conducted regarding the characterization of ICT in DTNs. ICT studies that use epoch-based method focus on node distributions, epoch lengths, movement directions and node speed. Most of the studies based on the above method show that the ICT of a node pair is distributed exponentially [4, 5, 8]. The authors in [8] also used the epoch-based method to determine whether the node parameter relates to the motion characteristics of nodes. However, their results not only lack general applicability, but also only focus on specific motion characteristics of mobile nodes, thereby making the application of performance analysis and protocol design difficult for DTNs.

Most stochastic-based studies used the Markov chain model to analyze the distribution and parameter characteristics of ICT between two mobile nodes [2, 3]. In [3], the ICT of a node pair is estimated to be an exponential distribution in RWP, RD and RW mobility models. However, many routing

algorithms of mobility models find fulfilling constraints of the Markov chain process difficult. Therefore, this paper focuses on the general stochastic-based method.
The determined ICT distribution between two taxis via real world traces are presented in [6], which provides empirical evidences that the ICT distribution is approximately an exponential distribution. However, experimental data are difficult to collect in real world mobility networks. Thus, we focused on ICT distribution and on the exponential parameter characteristics of node pairs in failure terminated testing. Specifically, the experiment will continue until the required number of contacts of those two mobile nodes is reached.

3 Preliminaries for IDCM

IDCM is a model that is based on reliability mathematics. In this section, after providing explanations for the basic notations and definitions of IDCM, we will introduce three assumptions to simplify the practical mobility environment and to facilitate modeling.

3.1 Notations and Definitions

We assume that a DTN has *N* mobile nodes existing in an area with size *S*. The located position of node *A* at time *t* is denoted as $L_A(t)$. We assume that each node has a circular radio transmission range equal to *R*. We define variable *r* as the number of contacts of two mobile nodes in failure terminated testing. We let $N(t)$ denote the contact times of two mobile nodes within the time interval (*0*, *t*] and define $P_n(t)$ as the probability of the contact *n* times of two mobile nodes within the time interval (*0*, *t*]. In addition, we denote $\pi(\lambda)$ as the prior distribution of exponential parameter λ in Bayesian statistics, $h(\lambda \mid T_1, T_2, \cdots, T_r)$ as the conditional posterior distribution of exponential parameter λ, and $|I(\lambda)|$ as the Fisher Information Matrix. The speed of a mobile node in failure terminated testing is randomly chosen from $[v_{\min}, v_{\max}]$, where $v_{\min} > 0,\ v_{\max} < \infty$.
Below we present several important definitions.
DEFINITION 1- ICT: $ICT(ICT_{(A,B)})$ is defined as the time that nodes *A* and *B* move into the transmission range of each other from the last time that they have moved out of the range of each other, i.e. $ICT_{(A,B)} = \min_t \{t : \|L_A(t) - L_B(t)\| \le R\}$. We let T_i denote the *i*th ICT between nodes *A* and *B*.
DEFINITON 2- λ: The instant contact rate $\lambda(\lambda_{(A,B)})$ is denoted as the average number of contacts of nodes *A* and *B* at time *t*, i.e. $\frac{N(\Delta t)}{\Delta t}$.

3.2 Three Assumptions for IDCM

- A small probability exists that any two mobile nodes can come into contact twice or more times in a short time Δt.
- The probability of two mobile nodes accomplishing one contact within Δt is approximately equal to $\lambda \Delta t$.
- The contacts of any two mobile nodes in the non-overlapping time durations are independent.

The above assumptions illustrate the main statistical characteristics of contacts between node pairs in a real DTN environment. For the first assumption, we deem that any node pair cannot accomplish more than one contact in a short time Δt considering that the motion states of mobile nodes are not able to change instantaneously. On the basis of the first assumption and **DEFINITION 2**, the second

assumption is put forward spontaneously. To our knowledge, motion of all mobile nodes in a DTN is independent. For example, the traces chosen by a taxi driver are not influenced by the other drivers. Thus, we introduce the third assumption.
These assumptions offer reasonable abstractions and facilitate the modeling of IDCM. An analysis of the ICT distribution by IDCM is provided in this paper.

4 ICT Distribution-based Contact Model

On the basis of life testing, we relate the historical contact information of a node pair to ICT distribution analysis. In this section, a reliability mathematical model IDCM is introduced and expounded. IDCM demonstrates that the ICT of a node pair is exponentially distributed and that the exponential parameter of a node pair only relates to the historical contact numbers and cumulative ICTs.

4.1 Distribution Analysis of ICT of a Node Pair

In this part, we consider a node pair *A* and *B*. We analyze the statistical characteristics of the contacts of nodes *A* and *B*, and then determine the distribution of ICT between nodes *A* and *B*.
Theorem 1: The Cumulative Distribution Function (CDF) of the contacts of nodes A and B within the time interval (0, t] is given by:

$$P_n(t) = \frac{1}{n!}\left(\lambda t\right)^n e^{-\lambda t} \tag{1}$$

where n is the number of contacts of nodes *A* and *B* within the time interval $(0, t]$.
Proof: By considering the assumptions above, we determine that when time $t+\Delta t$, $N(t) \le N(t+\Delta t)$. We define $N(t+\Delta t) - N(t)$ as the total contacts of node *A* and *B* within the time interval $(t, t+\Delta t]$. If $N(t+\Delta t) - N(t) = 1$, it means nodes *A* and *B* accomplish one contact within Δt. If $N(t+\Delta t) - N(t) = 0$, it indicates nodes *A* and *B* barely encounter each other within Δt. We can also determine that $P(N(t+\Delta t) - N(t) \ge 2) = o(\Delta t)$ on the basis of the first assumption.
From above, we can obtain the following equations:

$$P(N(t+\Delta t) - N(t) = 1) = \lambda \Delta t + o(\Delta t) \tag{2}$$

$$P(N(t+\Delta t) - N(t) = 0) = 1 - \lambda \Delta t + o(\Delta t) \tag{3}$$

By using the previous notations, we can identify that $P_n(t) = P(N(t) = n)$.
Thus according to (2) and (3) $P_n(t+\Delta t)$ can be obtained as follows:

$$P_n(t+\Delta t) = P_n(t)(1 - \lambda \Delta t + o(\Delta t)) + P_{n-1}(t)(\lambda \Delta t + o(\Delta t)) \tag{4}$$

We use (4) to derive the following equations:

$$\frac{P_n(t+\Delta t) - P_n(t)}{\Delta t} = \frac{\lambda(P_{n-1}(t) - P_n(t))\Delta t + o(\Delta t)}{\Delta t} \tag{5}$$

$$\frac{dP_n(t)}{dt} = \lambda(P_{n-1}(t) - P_n(t)) \tag{6}$$

After obtaining the ordinary differential equation for $P_n(t)$, we solve the resulting equation and obtain the result as **Theorem1**. ■
From above, we can see that the number of contacts of nodes *A* and *B* follows a Poisson distribution, which means that $N(t) \sim Possion(\lambda t)$.
Theorem 2: The Probability Density Function (PDF) of ICT between nodes *A* and *B* is given by:

$$f(x) = \lambda e^{-\lambda x} \tag{7}$$

We let the random variable *x* denote ICT and let *T* denote the lifetime of an experiment.

Proof: The ICTs are nonnegative random variables. The event {*x* > *T*} means that no contacts are present within time interval (*0*, *t*]; that is, {*x* > *T*} $=\{N(T)=0\}$. As $N(t) \sim Possion(\lambda t)$, we obtain $P(N(T)=0) = \frac{1}{0!}(\lambda T)^0 e^{-\lambda T} = e^{-\lambda T}$. Therefore, $F_x(T) = P(x \le T) = 1 - P(x > T) = 1 - e^{-\lambda T}$. As a result, the PDF of ICT between nodes *A* and *B* is represented as (7). ∎

Nodes *A* and *B* are randomly chosen from the investigative mobility models. Thus, we can conclude that the ICT between a node pair follows an exponential distribution, i.e. $ICT \sim \exp(\lambda)$.

4.2 Parameter Estimation

4.2.1 Point Estimation of the Exponential Parameter

In failure terminated testing, we focus on nodes *A* and *B.* We suppose that we can obtain *r* ICTs and assume that each T_i is independently distributed and exponential parameters are the same only for a node pair. We have demonstrated that $ICT \sim \exp(\lambda)$, i.e. $T_i \overset{iid}{\sim} \exp(\lambda)(1 \le i \le r, i \in Z)$. The following theorems analyze the point estimator and interval estimation of parameter λ.

Theorem 3: The point estimator of the exponential parameter in failure terminated testing is given by:

$$\hat{\lambda} = \frac{r}{\sum_{i=1}^{r} T_i} \tag{8}$$

Proof: Considering that $T_i \overset{iid}{\sim} \exp(\lambda)(1 \le i \le r, i \in Z)$, we can obtain the joint density function of those ICTs by using

$$f(T_1, T_2, \cdots, T_r) = \prod_{i=1}^{r} \lambda e^{-\lambda T_i} = \lambda^r e^{-\lambda \sum_{i=1}^{r} T_i} \tag{9}$$

Given that the exponential parameter λ depends on the historical contact information, we apply Jie Fletcher method to calculate $\pi(\lambda)$ [11]. Since that $\pi(\lambda) \propto |I(\lambda)|^{\frac{1}{2}}$ and that $|I(\lambda)|$ can easily be obtained by $|I(\lambda)| = -E(\frac{\partial^2 \ln f(T_1, T_2, \cdots, T_r \mid \lambda)}{\partial \lambda^2})$, we can obtain $\pi(\lambda) : \pi(\lambda) \propto |I(\lambda)|^{\frac{1}{2}} \propto \frac{1}{\lambda}$.

Therefore, we determine $h(\lambda \mid T_1, T_2, \cdots, T_r)$ as

$$h(\lambda \mid T_1, T_2, \cdots, T_r) = \frac{\pi(\lambda) f(T_1, T_2, \cdots, T_r \mid \lambda)}{\int_0^{+\infty} \pi(\lambda) f(T_1, T_2, \cdots, T_r \mid \lambda) d\lambda}$$
$$= \frac{(\sum_{i=1}^{r} T_i)^r \lambda^{r-1} e^{-\lambda \sum_{i=1}^{r} T_i}}{\Gamma(r)} \tag{10}$$

Thus, we can demonstrate that $h(\lambda \mid T_1, T_2, \cdots, T_r) \sim \Gamma(r, \frac{1}{\sum_{i=1}^{r} T_i})$. According to Bayesian estimation, we can obtain the estimator of the exponential parameter as follows:

$$\hat{\lambda} = E(\lambda \mid T_1, T_2, ..., T_r) = \frac{r}{\sum_{i=1}^{r} T_i} \tag{11}$$

■

From the above equations, we can conclude that the exponential parameter of mobile nodes relates to their historical contact numbers and cumulative ICTs. Thus, we cannot regard the exponential parameter of any two mobile nodes as the same. The above results are in strong contrast with the results of [3] and [7].

The point estimator cannot reflect the accuracy of the exponential parameter λ. Therefore, we analyze the sphere application of λ on the basis of the interval estimation in **Theorem 4**.

4.2.2 Interval Estimation of the Exponential Parameter

Theorem 4: In the failure terminated testing, the confidence interval with 1 − α probability of the exponential parameter of a node pair is given by:

$$\left[\frac{\chi^2_{1-\alpha/2}(2r)}{2\sum_{i=1}^{r} T_i}, \frac{\chi^2_{\alpha/2}(2r)}{2\sum_{i=1}^{r} T_i}\right] \tag{12}$$

Proof: We assume that $Z_i = 2\lambda T_i$. Given that $T_i \overset{iid}{\sim} \exp(\lambda)(1 \le i \le r, i \in Z)$, we identify that $Z_i \sim \chi^2(2)$. We can then obtain the confidence interval with 1 – α probability that same as in **Theorem 4**. ■

Through IDCM, we can determine both point estimator and confidence interval depending on the historical contact numbers and cumulative ICTs of nodes in failure terminated testing. Therefore, designing DTN protocols, as well as analyzing the performance of DTNs according to historical contact information, is important.

5 Simulations and Evaluations

In Section 5, we simulate IDCM with two theoretical models (RD and RWP) and two real world traces (Beijing taxi network and Pocket Switched Network (PSN)). And we also evaluate IDCM by using the RD and RWP mobility models.

In the simulations, we first mainly focus on the CDF and Complementary Cumulative Distribution Function (CCDF) of ICT between a node pair. The accuracy of the results of IDCM will be presented by the coefficient of determination R^2. IDCM is more superior and has a higher average R^2 than that of the model proposed in [6] and [11]. Network performance analysis concentrates on the message delay of RD and RWP models under unrestricted relay protocol.

5.1 Simulations

5.1.1 Parameter Settings of Simulations

In the simulations of RD and RWP mobility models, we set each simulation with 100 nodes moving in a 100m × 100m square. The nodes have transmission radio range R = 10m. The speed is set at $v_{\min} = 0, v_{\max} = 10$ m/s. We set the fixed number of contacts as r = 150 in failure terminated testing. We consider real mobility taxi traces for the simulation of real world mobility traces. In this simulation, about 10000 taxis, which are equipped with commercial GPS receivers and GPRS wireless communication modules, move in 25km×25km area in Beijing for a day (15 June 2010). We randomly choose a pair of taxis whose number of contacts is 35. We have downloaded data for the Pocket Switched Network (PSN) from the website [12]. The trace set includes four traces of Bluetooth sightings by groups of users carrying small devices (iMotes) for five days in the Computer Lab at University of Cambridge. We randomly choose two people and set the fixed number of contacts at 150.

Fig.1 Simulation and theoretical results of RD mobility model.

Fig.2 Simulation and theoretical results of RWP mobility model.

Fig.3 Simulation and theoretical results of Beijing taxi network.

Fig.4 Simulation and theoretical results of PSN.

Mobility Model or Trace	R^2
RD	0.9703041
RWP	0.9515668
Beijing Taxi Network	0.9542103
Pocket Switched Network	0.9351140

Tab. 1 R^2 obtained by IDCM.

5.1.2 The Coefficient of Determination

We apply the coefficient R^2 to identify the significance between modeled and observed values, as shown below

$$R^2 = 1 - \frac{\sum_k (f_k - p_k)^2}{\sum_k (f_k - \overline{f})^2} \tag{13}$$

where $f_k = \frac{\sum_{i=1}^{k} T_i}{\sum_{i=1}^{r} T_i} (k = 1, 2, \cdots, r)$, denotes the observed values. Each value has an associated modeled value $p_k = P(Z < \sum_{i=1}^{k} T_i) = 1 - \exp(-\hat{\lambda} \sum_{i=1}^{k} T_i)(k = 1, 2, \cdots, r)$. Here, r is the number of contacts of two mobile nodes in different mobility models, $\hat{\lambda}$ is the exponential estimator and Z is the random variable within time interval $(0, \sum_{i=1}^{r} T_i]$. The mean of the observed values in the mobility models is $\overline{f}$. Thus, the larger the value of R^2 is, the more accurate the model becomes.

5.1.3 Simulation Results

We validate the accuracy of IDCM by comparing the simulation and theoretical results in the RD, RWP and real world mobility traces. As shown in **Figs. 1-4** and **Tab. 1**, the theoretical results of the proposed method match well with the simulation results because the coefficient of determination $R^2 >$ 0.935 in both theoretical mobility models and real world mobility traces. We illustrate the empirical estimation of CCDF of ICT in the lin-log scale, in which we use blue lines to represent the theoretical results and red circles to represent the simulation results. **Figs. 1-4** show that the simulation results, which are closely matched with the theoretical result, exhibit a plummeting trend. Therefore, we can denote that the ICT of a node pair has an exponential distribution in the RWP, RD, as well as Beijing taxi network and PSN. These results are in contrast with the result of the power law distribution in [1]

and [7].
In [6] and [11], the ICTs of all node pairs are assumed to be exponentially distributed. Thus, a model is constructed to determine the exponential parameter of node pairs through aggregate ICT statistics. To obtain the ICT of each node pair, we compare the R^2 of IDCM with the R^2 of the model proposed in [6]. **Tab. 2** shows the exponential parameters obtained through the approach presented in [6].

Data Set	λ
RD	0.000654144
RWP	0.000585178
Beijing Taxi Network	0.00077527
Pocket Switched Network	0.00092036

Tab. 2 λ obtained by aggregate ICT statistics.

Figs.5 to **8** illustrate the comparison results of R^2 between IDCM and that in [6]. Each dot is plotted by using the serial number of a node pair on the horizontal axis and the value of R^2 on the vertical axis. The horizontal blue line represents the average R^2 of the network. The figures show that the average R^2 of IDCM for the theoretical models and real traces is greater than that of the other model. For example, the average R^2 of IDCM in the Beijing taxi network and PSN is 0.822 and 0.789, respectively, which are14.64% and 15.01% higher than R^2 of the model in [6]. IDCM can obtain the ICT distribution of a node pair with higher accuracy than that of the model in [6], thus denoting that IDCM is better than the model that uses the aggregate ICT statistics in terms of depicting contacts between node pairs.

Fig.5 Comparison of R^2 results for RD.

Fig.6 Comparison of R^2 results for RWP.

Fig.7 Comparison of R^2 results for Beijing taxi network.

Fig.8 Comparison of R^2 results for PSN.

5.2 Evaluations

5.2.1 Message Delay Analysis

Message delay is the time needed to send a message from the source to the destination. The average message delay reflects the entire network performance. The authors in [12, 15, 16] studied message delay in wireless networks, where ICTs of all node pairs independently share an exponential distribution depending on two variables, the network capacities *N* and the contact intensity λ .

$$E(T)=\frac{1}{\lambda(N-1)}\sum_{i=1}^{N-1}\frac{1}{i}=\frac{1}{\lambda(N-1)}(\log(N-1)+\gamma+O(\frac{1}{N})),\gamma\approx 0.57721 \qquad (14)$$

The above equation is a decreasing function of λ with a given *N*.
Nonetheless, (14) strictly requires ICTs of all node pairs to be identically exponentially distributed. Thus, we introduce several notations to expand the application of (14) into a network where the ICTs of all node pairs are exponentially but not identically distributed:

- $\lambda_{\max}$ and $\lambda_{\min}$, which are the maximum and minimum of set { $\lambda_{(A,B)}$ } $(1\le A,B\le N)$;
- *T*, which is the message delay of a wireless network;

◆ $E(T^{+})$ and $E(T^{-})$, which are the values of (14) using $\lambda_{\min}$ and $\lambda_{\max}$, respectively.

As shown in (11), the exponential parameter λ represents the average contact intensity of a node pair in a period. If all contact intensities $\lambda_{(A,B)}$ of the node pairs are between $\lambda_{\min}$ and $\lambda_{\max}$, then the expected message delay should be between the maximum and minimum expected message delays:

$$E(T^{-}) \le E(T) \le E(T^{+}) \tag{15}$$

The upper bound of the expected message delay can be obtained by using (15).

We have tested and verified (15) by using two theoretical models (RWP and RD), in which the testing results correspond to (15).

5.2.2 Testing and Verification

A) Parameter Settings of Evaluations

We have simulated the RD and RWP models for 432000s in which nodes are moving in a 4000m× 4000m square area. The nodes have a transmission radio range R=50m. For both models, speed (in m/s) is chosen uniformly in $[v_{\min}, v_{\max}]$ = [1, 2.8].

Fig.9 Evaluation results of RD and RWP mobility models.

We set the network capacity with 20, 40, 60, 80 and 100 nodes and obtain the upper bounds of the expected message delay.

B) Evaluation Results

As shown in **Fig.9**, we test and verify (15) by comparing the theoretical upper bounds and experimental results of RD and RWP. We use blue dots to represent the theoretical upper bounds of the expected message delay and red dots to represent the experimental results. **Fig.9** shows that the simulation results are all below the theoretical upper bounds. Therefore, ICT calculated through IDCM has good accuracy and exhibits good performance in message delay analysis.

6 Conclusions

In this paper, we studied the ICT distribution of node pairs in mobility models and real world traces. On the basis of reliability mathematics and life testing, we have constructed the IDCM, through which we have proven that the ICT distribution is exponential. The proposed model also suggests that the historical contact information of node pairs should not be neglected because the exponential parameter can be obtained only if the historical contact numbers and cumulative ICTs of node pairs are determined. Through theoretical analysis, proofs and extensive experimental results, we have concluded that the IDCM determines statistical the characteristics of ICT and that the IDCM provides highly precise exponential distribution, which is in contrast with the power law distribution of other studies. Thus, IDCM is instructive and important in further studies on DTNs.

In our future work, we plan to delve deeper to random process modeling for the realistic emulation of mobility networks. We also plan into explore ways of adapting IDCM to improve the existing network performance analysis. Finally, IDCM increases interests of the research community regarding the optimization of existing algorithms and protocols.

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Fig.1 Simulation and theoretical results of RD mobility model

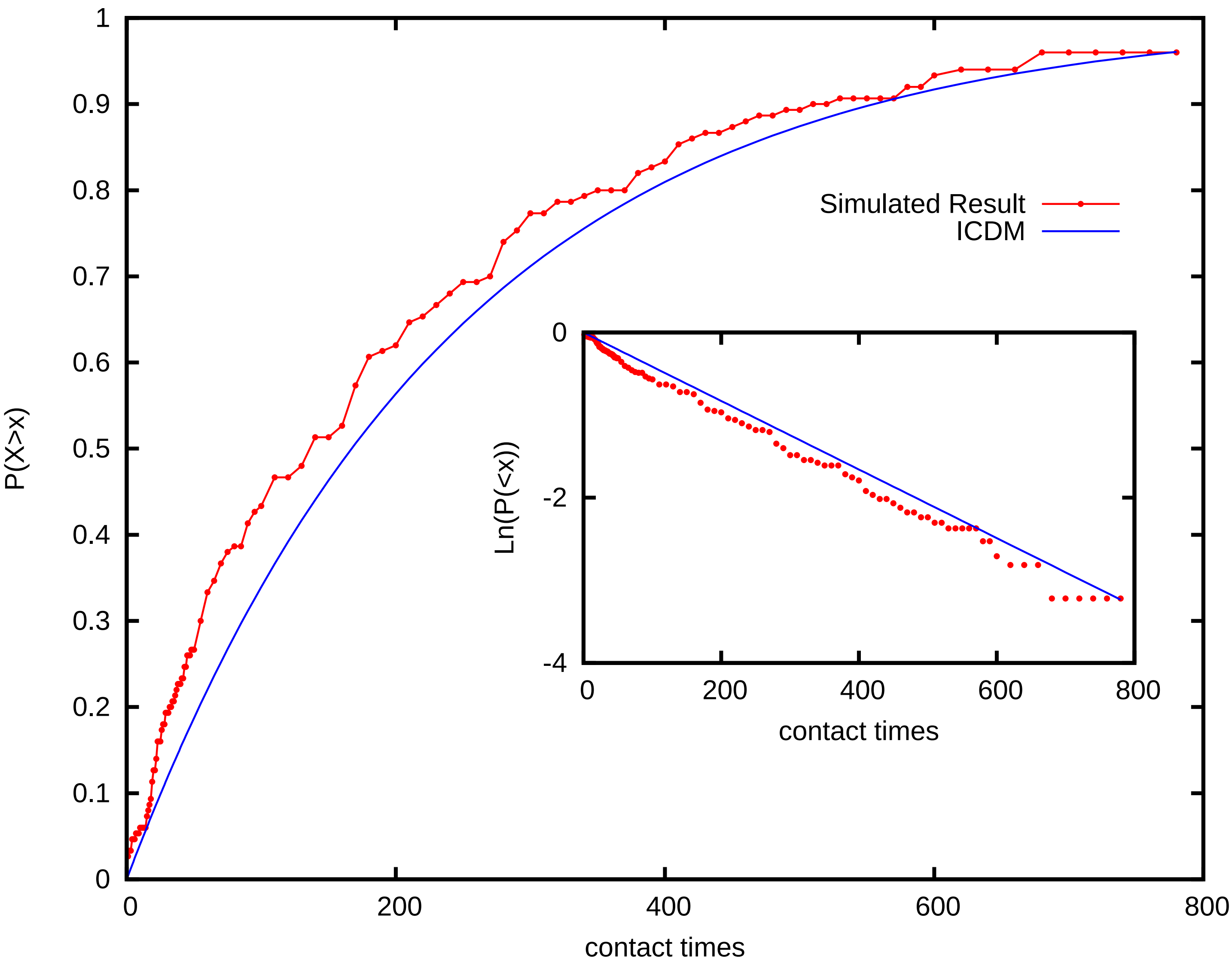


Fig.2 Simulation and theoretical results of RWP mobility model

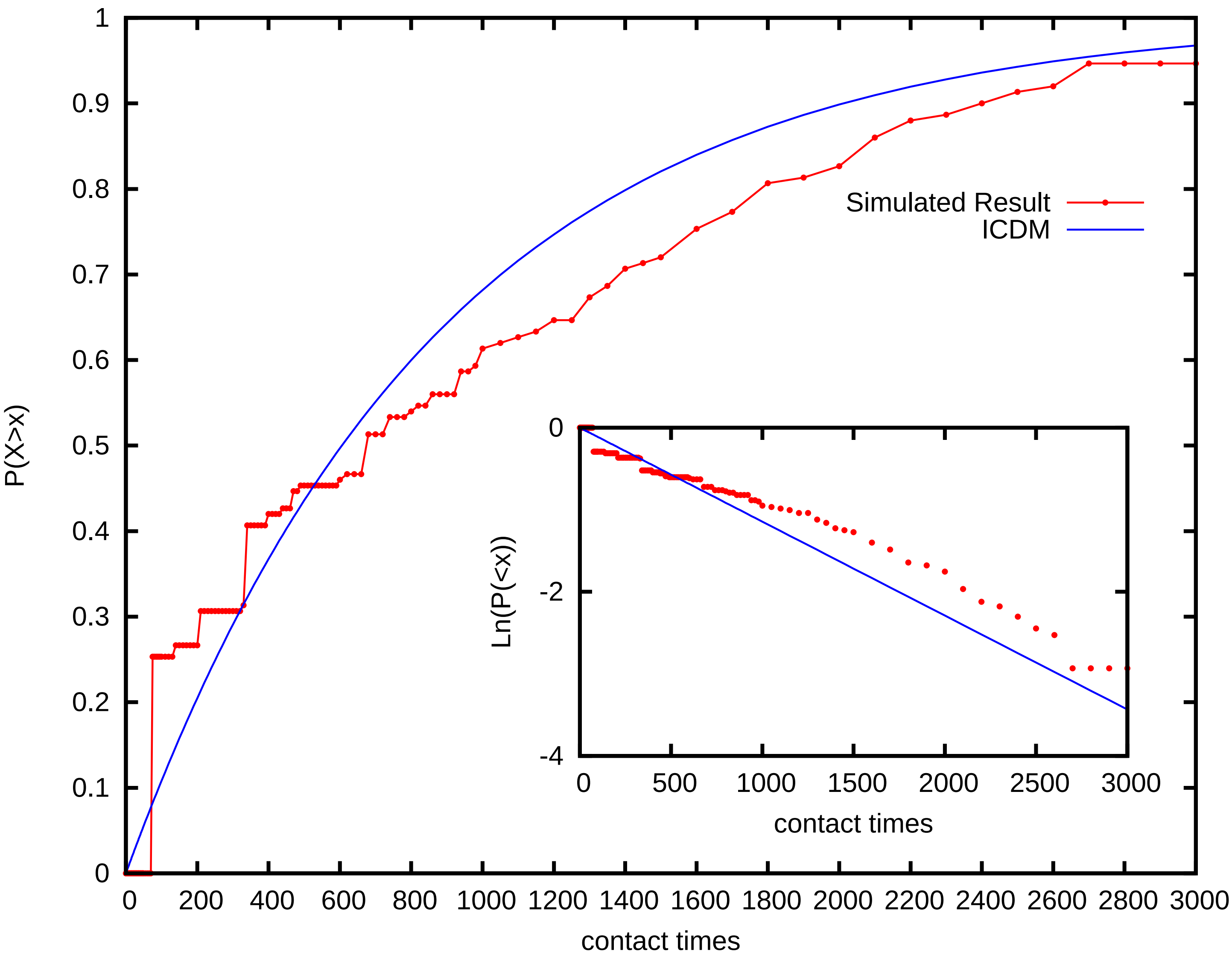


Fig.3 Simulation and theoretical results of Beijing taxi network

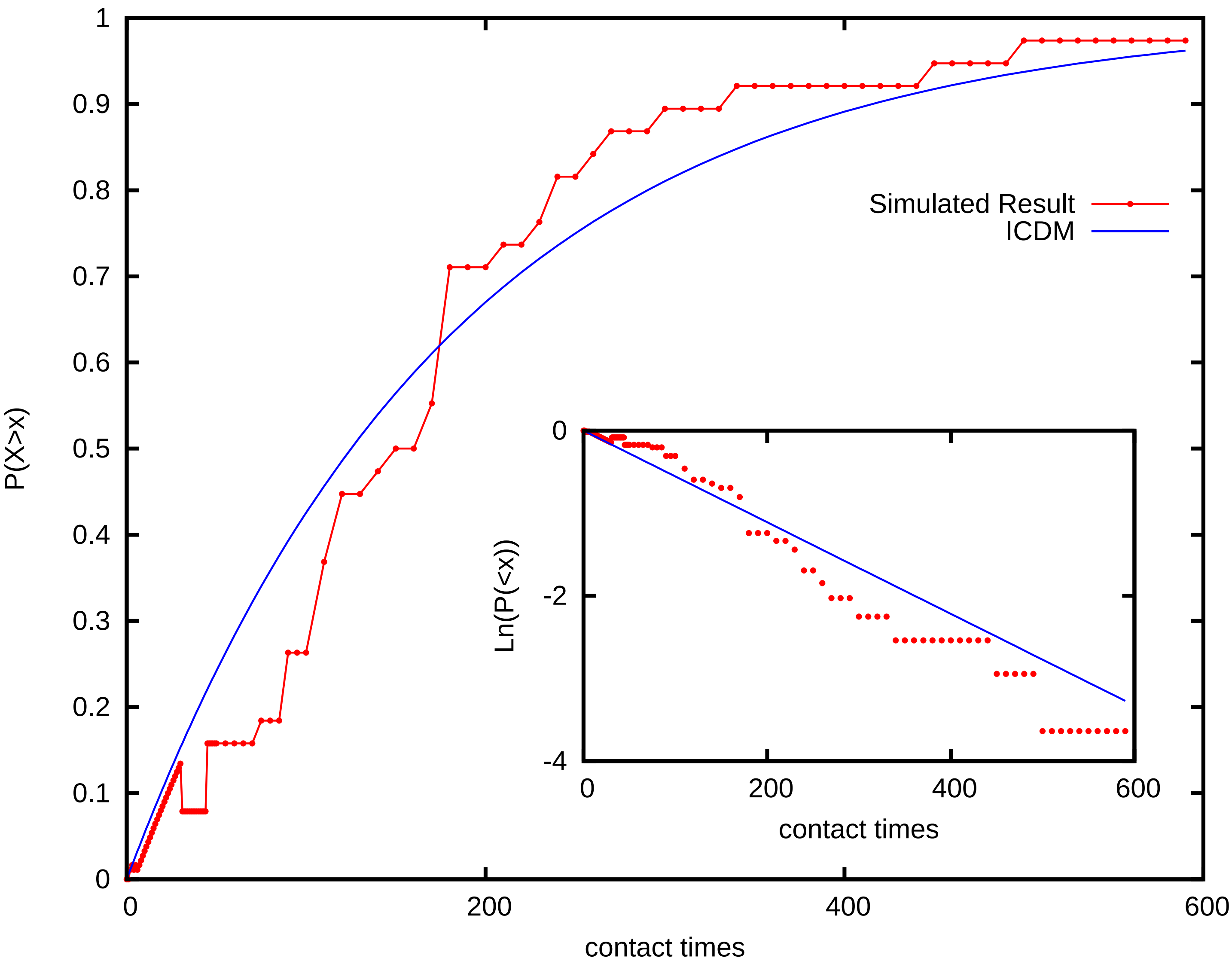


Fig.4 Simulation and theoretical results of PSN

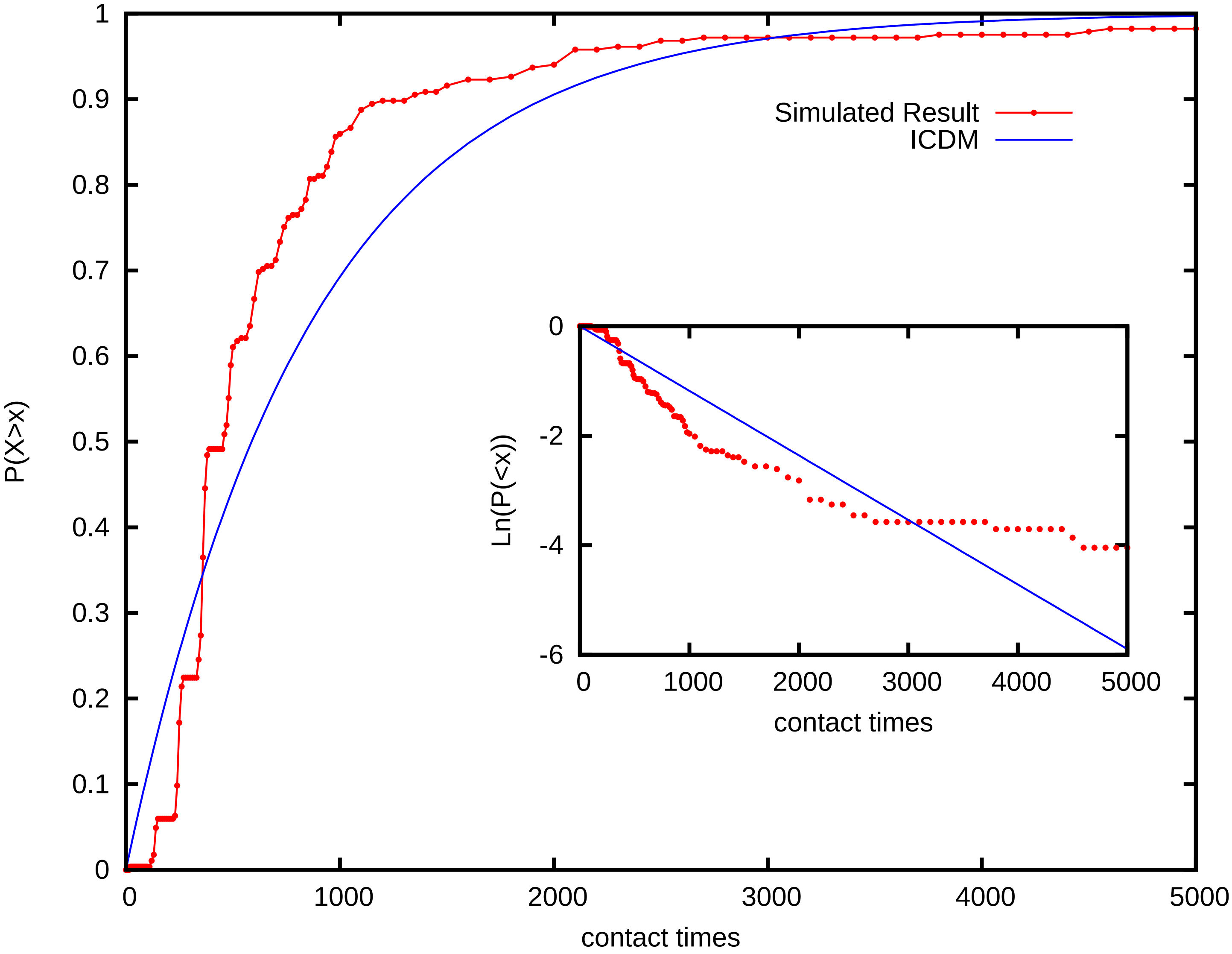


Fig.5 Comparison of results for RD

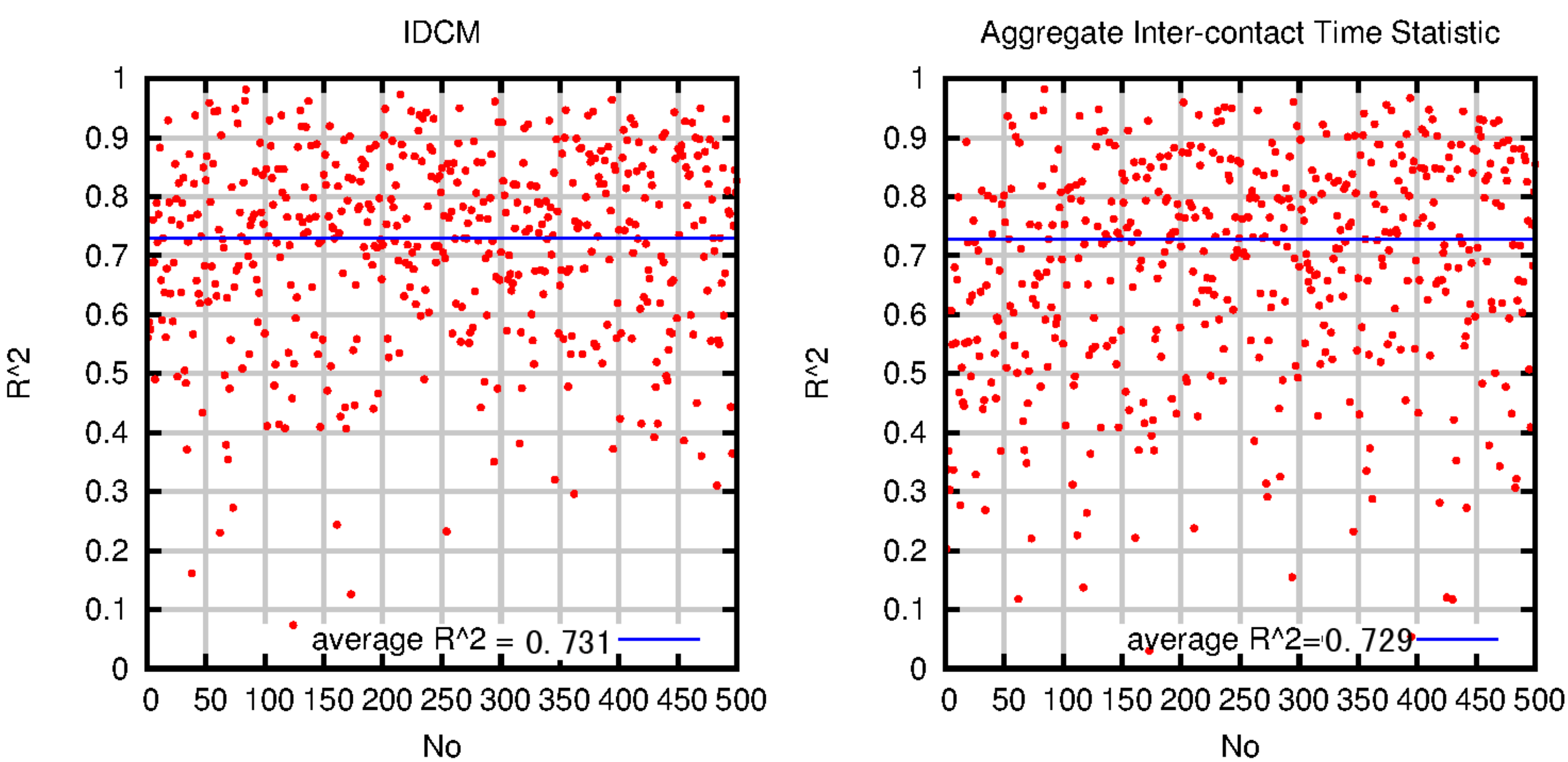


Fig.6 Comparison of R^2 results for RWP

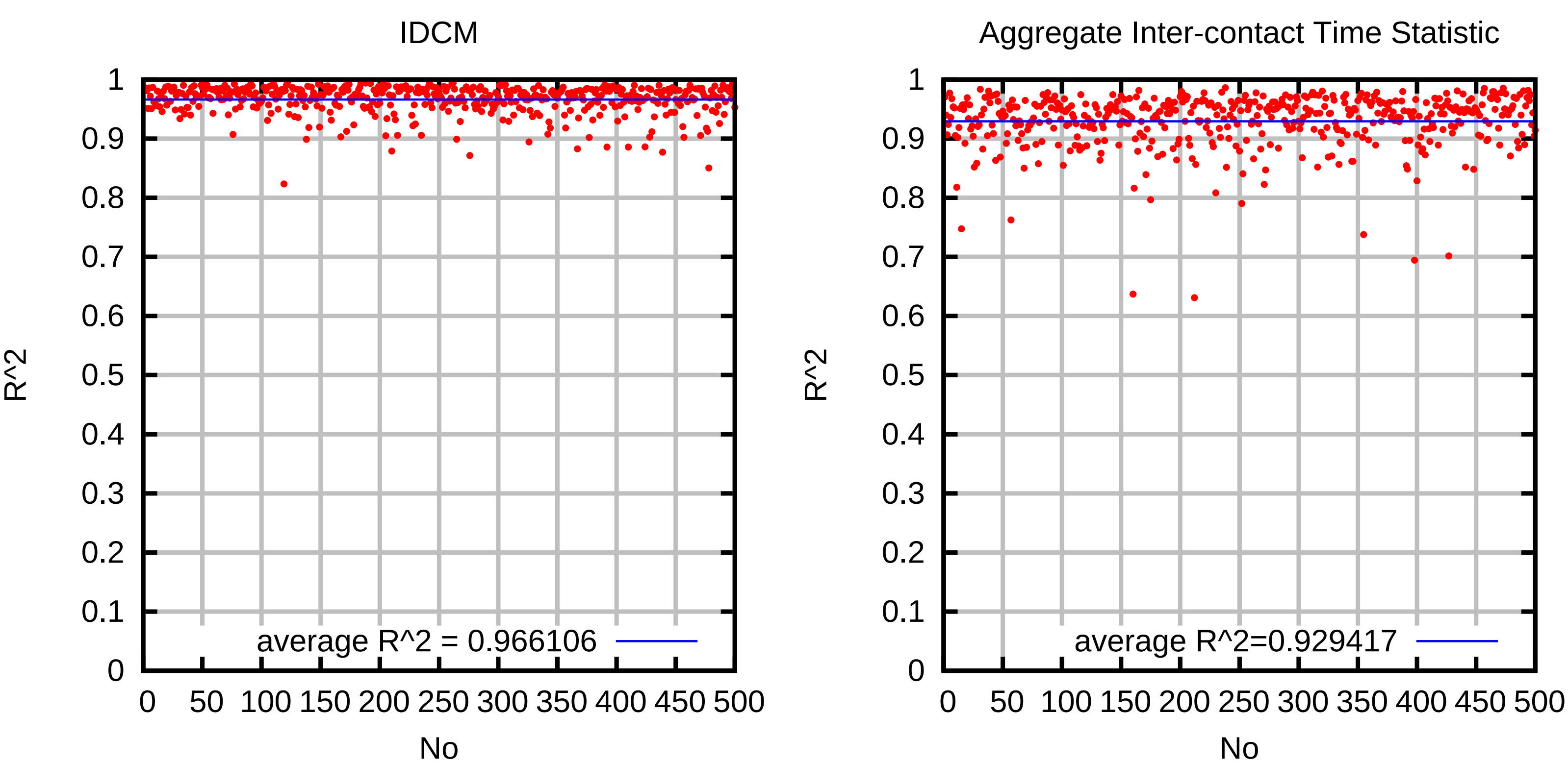
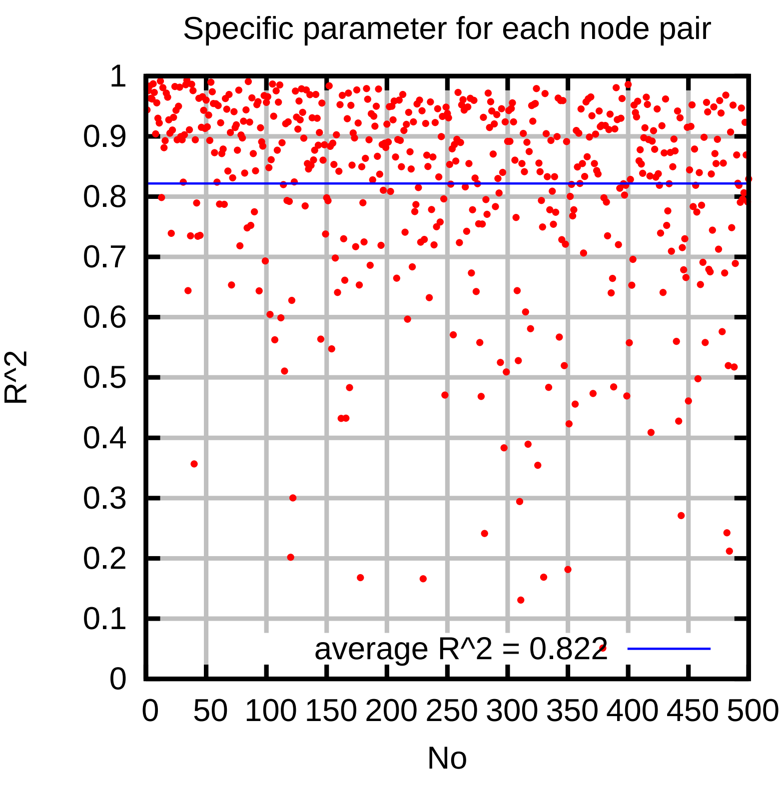


Fig.7 Comparison of R^2 results for Beijing taxi network



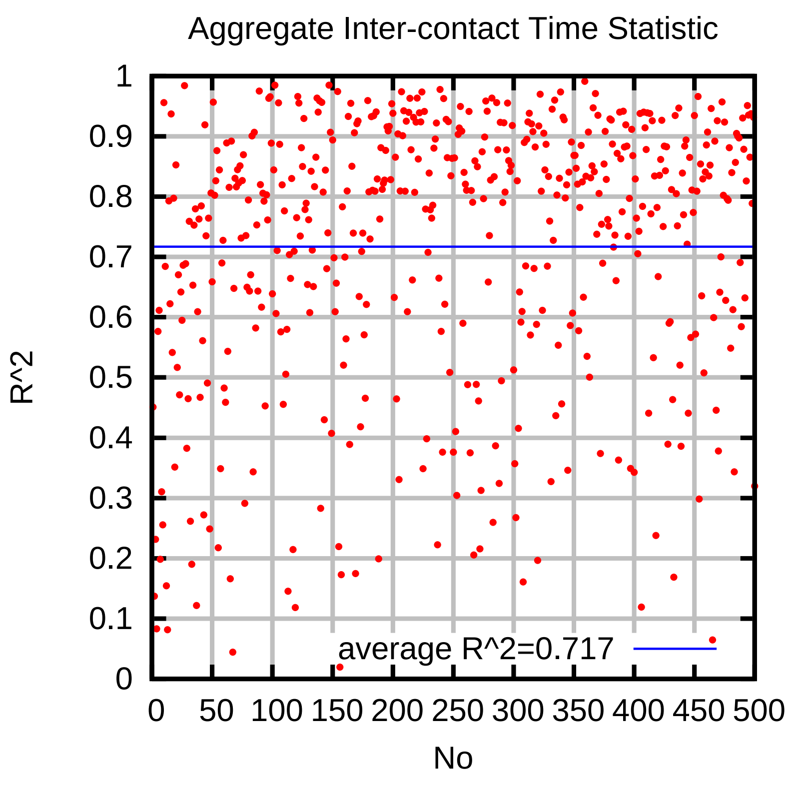


Fig.8 Comparison of R^2 results for PSN

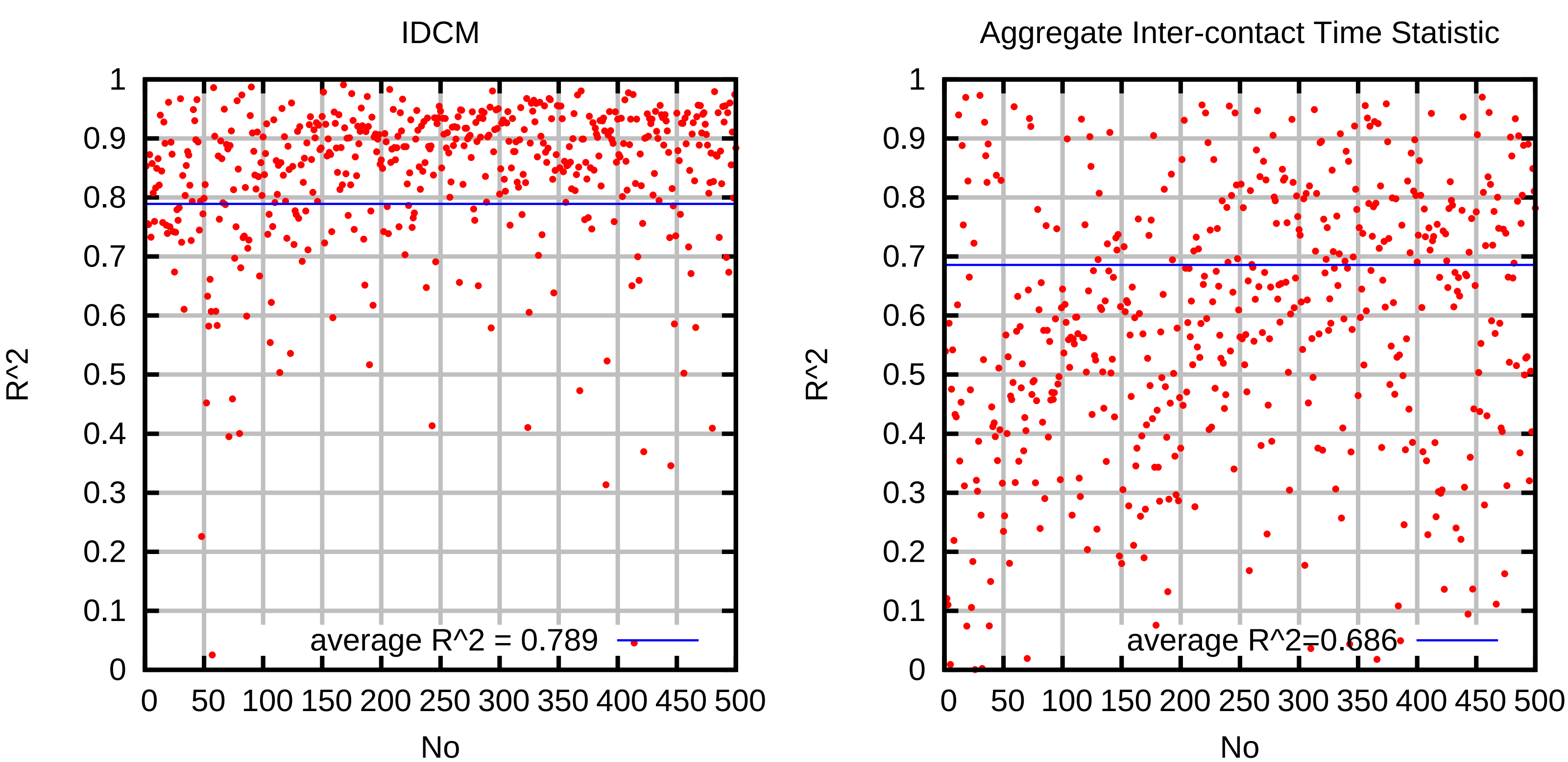


Fig.9 Evaluation results of RD and RWP mobility models