# Impact of Super-Diffusive Behavior on Routing Performance in Delay Tolerant Networks

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***Abstract*— Motivated by the recent findings of super-diffusive patterns in mobility traces, we investigate the impact of super-diffusive behavior of mobile nodes on contact-based metrics and performance metrics of routing protocols in delay tolerant networks (DTNs). We show that diffusive properties make huge impact on the performance of routing protocol – message delivery ratio and delay of delivered messages, and existing models such as random waypoint models or Brownian motion models lead to overly optimistic or pessimistic results when diffusive properties are not properly captured. In addition, we point out that existing contact-based metrics are unable to differentiate between varying degrees of routing performance under different diffusive mobility patterns, and then propose to use the number of new contacts as a fare more effective metric, especially for scenarios in which message routing/forwarding is built upon contacts among mobile nodes. Our work in this paper suggests that the diffusive behavior of mobile nodes should be taken into account, for the design and the performance evaluation of network protocols in DTN.**

## I. INTRODUCTION

Generating realistic movement patterns of mobile nodes by sound mobility models is crucial in the performance evaluation of routing protocol in delay-tolerant networks (DTNs). Mobility models that cannot capture the key characteristics of mobile nodes properly will lead to misleading decision and design guidelines.

Recently, [7], [9] have found ‘super-diffusive’ [12] movement patterns in numerous GPS traces as well as access points (AP) based traces. Super-diffusive behavior implies that mobile nodes tend to spread out quicker than typical random walks categorized by normal diffusion [12]. In [7], [9], various mobile nodes including humans, zebras and buses have been shown to follow super-diffusive movement patterns. In particular, for human traces, different movement patterns such as walking, running, inline-skating and bicycling have been shown to display different degrees of diffusive properties (different rate of ‘spreading out’).

In the literature, performance evaluation of routing protocols has been extensively studied in MANETs, with only a handful of studies for DTNs. [1] investigates performance evaluation of DTN by using random waypoint models (RWP), but diffusive property and other key characteristics of real mobility patterns are very different from those of RWP [7], [9]. On the other hand, authors in [2], [4], [10] have proposed several metrics for performance evaluation study in MANETs. Although these work provide extensive results, they are mainly for MANET, not for DTN. For example, route-related metrics [10] (route change rate, route duration) and link-related metrics [4], [10] (link duration and link change rate) are not adequate for delay-tolerant networks, as the chance of establishing a link is rare and it is very unlikely that an end-to-end path exists at any time in DTNs.

In this paper, we examine how different diffusive properties of mobile nodes impact contact-based metrics and the performance of routing protocols in DTNs. First, we propose to consider a new contact-based metric, tailored to routing performance study in DTN. We show that contact rate and contact duration, recently proposed pairwise contact based metrics in [6] for DTN, are unable to differentiate varying degrees of routing performance in DTN. Instead, in this paper, we point out that each contact between mobile nodes under study does not necessarily contribute to successful message delivery/transfer in DTNs. Motivated by this, we distinguish between *the number of new contacts* and the number of total contacts, and find that the number of new contacts is far more relevant metric in performance study of DTN routing protocols. Our results show that the number of new contacts is in direct relationships with performance metrics such as message delivery ratio and delay of delivered messages.

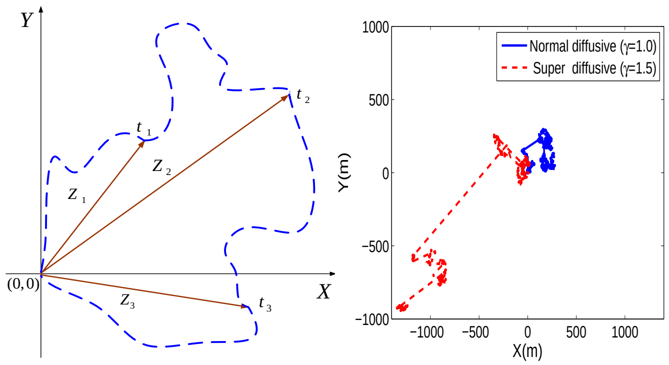
Second, equipped with our newly proposed metric, we study performance evaluation in DTN by using more realistic movement patterns that correctly reflect diffusive properties of mobile nodes. Specially, we use epidemic routing protocol [15] for performance test in $ns$-2, and employ a class of Lévy walk models that are easy to generate, versatile, and known to capture various diffusive properties as observed in real traces [7], [9]. Intuitively, mobile nodes with more diffusive property will cover larger area over the same time duration when compared to less diffusive ones, which in turn affects how many new nodes a given node will encounter over time, i.e., the number of new contacts.

Our results in this paper show that diffusive properties make a huge impact on performance of DTN routing protocols, and existing mobility models are mostly either too optimistic or too pessimistic, suggesting that we should be more careful in capturing the correct diffusive behavior of mobile nodes for the purpose of correct evaluation of routing protocols.

## II. PRELIMINARIES

In this section, we present background on the mean square displacement – a metric to capture the rate at which mobile nodes spread out, super-diffusion, Lévy walk models, and provide a brief summary of our previous works [7], [9], in which we report super-diffusive behavior in real mobile traces.

### A. *Mean Square Displacement (MSD)*



(a) MSD computation (b) Super-diffusive node

Fig. 1. MSD computation and sample trajectories of two nodes with different diffusive properties. Two nodes moving with the same speed (1.34 m/s) are simulated over the same duration (10000 sec).

The movement of a mobile node can be characterized by measuring how far they are away from its starting point after time $t$. This diffusive property can be properly captured by the mean square displacement (MSD) [3], [12]. MSD is defined as follows. When we denote $Z_t \in \mathbb{R}^2$ as the position of the mobile node at time $t$, the MSD becomes $M(t) \triangleq \mathbb{E}\{\|Z_t - Z_0\|^2\}$ (i.e., the second moment of the displacement $\|Z_t - Z_0\|$ between the current position at time $t$ and the position at time 0). For a class of isotropic random walks with finite step-length variance ($\sigma_L^2 < \infty$), the MSD will grow linearly with $t$, i.e,. $M(t) \sim t$, provided that the speed of the mobile node is $O(1)$ (or constant). A classical example of this case is the 2-D Brownian motion process whose variance grows linearly with $t$. Figure 1(a) illustrates how MSD is measured. As a mobile node starting from the origin follows the trajectories above, we collect the displacement at each time instant $t_i$. Then, we investigate how MSD grows with time $t$ to find out the diffusive property of mobile nodes.

### B. *Super-Diffusion*

When the step-length has infinite variance ($\sigma_L^2 = \infty$), the mobile node tends to quickly spread out since longer step-lengths are generated more often. This behavior is called *super-diffusion* [8], [16], while for $\sigma_L^2 < \infty$ it is called normal diffusion. To quantify the degree of diffusive properties of mobile nodes, we investigate the slope ($\gamma$) of $M(t)$ in a log-log scale (i.e., $M(t) \sim t^\gamma$). For a normal diffusive case, $\gamma = 1$, while we have $\gamma > 1$ for super-diffusive case. In particular, ‘ballistic’ movement corresponds to $\gamma = 2$. Figure 1(b) shows typical sample trajectories of two nodes with different diffusive properties (different $\gamma$). While both nodes have the same speed (1.34 m/s) and run over the same duration (10000 sec), the super-diffusive node ($\gamma = 1.5$) spreads out from the origin much further than the normal-diffusive node ($\gamma = 1.0$).

### C. *Super-diffusive Property in Real Traces*

Super-diffusive property of mobile nodes has been observed in numerous GPS traces as well as AP-sampled traces [7], [9]. Table I summarizes the super-diffusive properties, in terms of the slope of MSD $\gamma$, observed in several mobility traces. For more details, see [7], [9].

| Node | Movement | MSD slope ($\gamma$) | Diffusion |
|---|---|---|---|
| human | walking | 1.48 | super-diffusive |
| human | running | 1.70 | super-diffusive |
| human | inline-skating | 1.88 | super-diffusive |
| zebra | walking & running | 1.95 | super-diffusive |
| bus | n/a | 1.55 | super-diffusive |

TABLE I

DIFFUSIVE PROPERTY OF MOBILE NODES FROM REAL GPS TRACES. IN ALL CASES, MSD INCREASES FASTER THAN LINEAR ($\gamma > 1$).

### D. *Lévy Walk Models*

A set of Lévy walk models can be used to generate various degrees of diffusive properties. Unlike other mobility models that would require subtle choice of several parameters to control diffusive properties, Lévy walk can directly control the degree of super-diffusive properties by adjusting the exponent of step-lengths $\mu$ (single parameter) [7], [9]. The Lévy walk model is a class of random walk models whose step-length distribution is heavy-tailed, i.e., the step-length density is characterized by

$$f_L(l) \sim l^{-\mu}, \quad 1 < \mu < 3,$$

where $\mu > 1$ is required for any valid probability density function. In particular, there exists a clear-cut relationship between $\mu$ and the MSD ($M(t) \sim t^\gamma$) slope $\gamma$ as follows [13].

$$M(t) = \mathbb{E}\{\|Z_t - Z_0\|^2\} \sim \begin{cases} t & \text{if } \mu > 3, \\ t^{4-\mu} & \text{if } 2 < \mu \leq 3, \\ t^2 & \text{if } 1 < \mu \leq 2, \end{cases}$$

This relationship implies we can generate mobility patterns with varying degrees of diffusive behaviors, with $\gamma$ ranging from 1 to 2 by controlling the step-length exponent $\mu$. Note that $\sigma_L^2 = \infty$ for any $\mu < 3$, while $\mu = 3.0$ corresponds to Brownian motion with finite step-length variance.

## III. METRICS AND SIMULATION SETUP

In this section, we first explain the contact-based metrics and other metrics used in the performance evaluation of routing protocols. We also provide details on simulation setup.

### A. *Metrics*

*1) Contact-based metrics:* In the performance evaluation of DTN routing protocols, ‘*contact*’ is the most important factor as nodes have an opportunity of sending and receiving packets only when they are within the transmission range with other nodes. We say that there is a ‘contact’ or they ‘meet’ when the distance between two nodes is less than their common transmission range $r$. Among many contact-related metrics, we first consider the number of contacts (over a given time duration) and contact duration as used in [6]. We distinguish between the number of new contacts and total contacts among nodes. Specifically, we also observe how the number of new contacts increases as time goes on. Below are the three metrics under our consideration.

- **The total number of new contacts**: Whenever a pair of nodes meet for the first time, this metric is incremented by one. Future contacts after the first meeting between this pair of nodes are not counted. We consider this metric as new contacts are more likely to contribute to successful message delivery than the repeated contacts to the same nodes.
- **The total number of contacts**: Whenever any pair of nodes meet, this metric is incremented by one.
- **The total contact duration**: This metric sums all the contact durations among nodes. For example, if node A is in contact with node B for $10$ minutes and with node C for $20$, the total contact duration is $30$ minutes regardless of the case that node A is in contact with node B and C at the same time.

*2) Metrics for the performance of routing protocol:* We consider the epidemic routing protocol [15] in our study. While there are a number of other routing protocols developed for DTNs [5], most of them are variants of the epidemic routing protocol with several tuning knobs for performance tradeoff. Epidemic routing uses a store-carry-forward strategy in sending and receiving a packet. When two nodes come into contact, each node copies a message to other ('infect') if the other node doesn't have it already. After exchange of message, each node will get all the messages it has not received so far [15].

We use the following key metrics to assess the performance of epidemic routing protocol [1].

- **Message delivery ratio:** This metric indicates the percentage of packets that are delivered to the destination after they are sent from the source.
- **Delay of delivered messages:** This metric shows the time taken from the source to destination after packet is sent. We only take into account packets that are successfully delivered to their destination, as we cannot calculate the delay of undelivered messages.

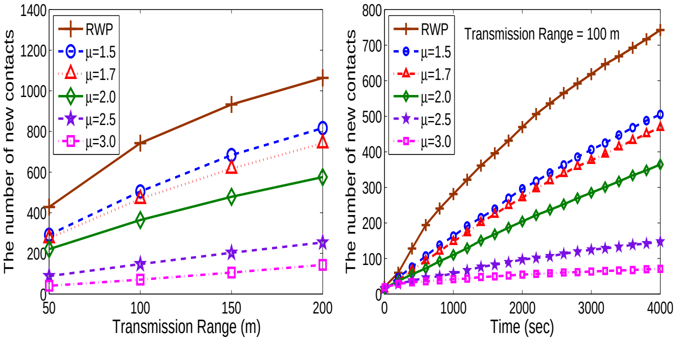
### B. Simulation setup

Our $ns$-2 simulation setup is as follows. $50$ mobile nodes move around according to a given mobility model of our choice with constant speed ($1.34$ m/s) in an area ($1500m \times 1500m$). We assume that nodes continuously move around and do not pause, as our main focus lies in the impact of mobility pattern (super-diffusive) on routing protocol performance. 45 (out of 50) nodes are selected as message source/destination nodes, and each of $45$ nodes sends out one message (packet) to $44$ other nodes, i.e., a total of $45 \times 44 = 1980$ messages are sent out for delivery during the simulation. We set the total simulation time to $4000$ seconds and the maximum buffer size of each node to 500 messages. The maximum number of hops a message can travel is set to 5 hops. We gradually increase the 'density' of node coverage by changing their transmission range $r$ from 25$m$ to 200$m$. For the underlying mobility model, as mentioned before, we use a set of Lévy walk models with different $\mu$ for the step-length distribution to reflect different degrees of diffusive behaviors. We also use RWP as a reference model and for comparison purpose. All simulation results are shown by averaging over $10$ independent trials.

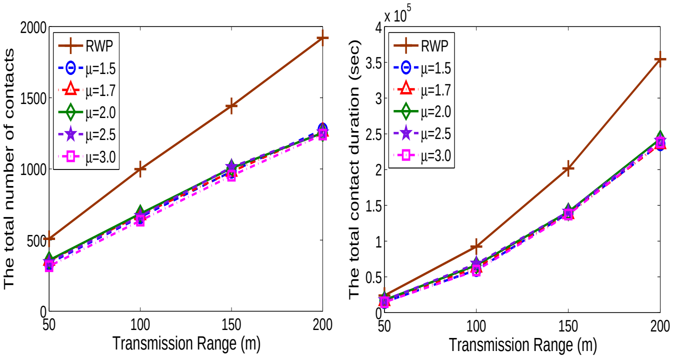
## IV. NUMERICAL RESULTS

### A. Impact of Different Diffusive Behavior

In this section, we investigate the impact of diffusive properties of mobile nodes on the contact-based metrics among nodes as proposed in Section III-A. All the mobile nodes under consideration are assumed to follow the same mobility model of our choice. We will consider heterogeneous mix of mobility models for nodes later in this paper.



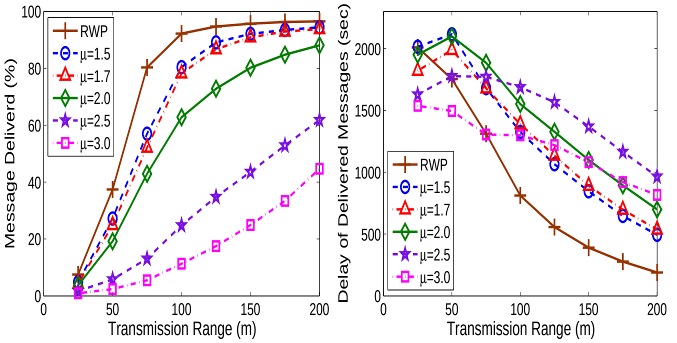
(a) The number of new contacts (b) New contacts with time $t$



(c) The total number of contacts (d) The total contact duration

Fig. 2. Impact of diffusive properties on several contact-based metrics: (a) total number of new contacts among all nodes after simulation time $t = 4000$ seconds; (b) total number of new contacts during time interval $t$; (c) total number of contacts (including those among the same pair of nodes) after $t = 4000$ seconds; (d) total contact duration after $t = 4000$ seconds. Metrics that do not capture new contacts ((c) and (d)) perform the same regardless of the different diffusive behaviors, while metrics based on 'new contact' are sensitive to varying degree ($\mu$) of diffusive behaviors. When $\mu$ is small, nodes tend to spread out further from the starting points, thus creating larger number of new contacts with other nodes.

*1) Contact-based Metrics:* Figure 2 shows how different diffusive properties make an impact on contact-based metrics. Note that the number of total contacts in (c) and the total contact duration in (d) are almost the same for all class of Lévy walk models with different diffusive behaviors under our consideration ($\gamma$ ranges from 2 to 1, as $\mu$ increases from 1.5 to 3.0), except RWP model for the same transmission range $r$. However, the number of new contacts in Figure 2(a) shows the considerable differences with different diffusive properties. This means that the number of new contacts is more relevant metric to capture the varying degree of diffusive behaviors. In addition, Figure 2(a) also reveals that (i) when mobile nodes diffuse faster (smaller $\mu$, or equivalently, larger $\gamma$), they are more successful in encountering new nodes, and (ii) for mobile nodes with larger $\mu$ (diffuse slower), most of their contacts are with the same nodes nearby (since the total number of contacts are the same from (c)). Figure 2(b) further supports this observation; mobile nodes with faster diffusive property keep reaching out and meet more new nodes as time goes on. The number of new contacts for faster-diffusive nodes increases sharply, while nodes with slower-diffusive behavior (e.g., $\mu = 3.0$) rarely meet new nodes during the simulation time ($t = 4000$ seconds).



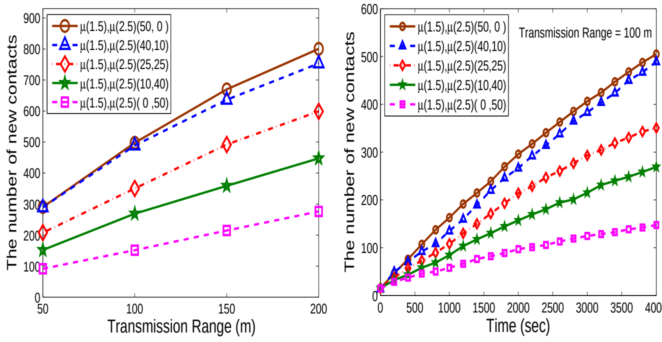
(a) Message Delivery Ratio (b) Delay of Delivered Messages

Fig. 3. Impact of diffusive properties on the performance of epidemic routing. As the nodes tend to diffuse faster (smaller $\mu$), the message delivery ratio becomes larger and the delay for the successfully delivered message becomes also smaller in general.

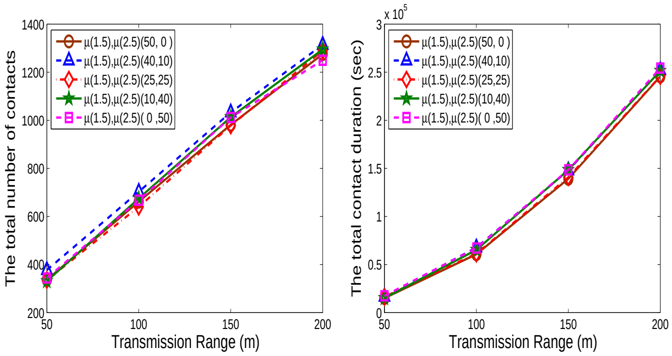
*2) Performance of Epidemic Routing Protocol:* Figure 3(a) shows the average message delivery ratio of a class of Lévy walk models with different $\mu$ and RWP model. As can be seen clearly, varying degrees of diffusive behavior (parameterized by $\mu$) result in widely different network performance. In particular, we see that faster diffusive behavior of mobile nodes (smaller $\mu$) gives higher delivery ratio under the same transmission range. This is largely due to the increase in the number of new contacts with other mobile nodes for smaller values of $\mu$, as nodes tend to reach out more aggressively. Note that the ordering of message delivery ratio in Figure 3(a) is exactly the same as that of the number of new contacts shown in Figure 2(a).

Figure 3(b) shows the delay of successfully delivered messages under different diffusive mobility patterns. For smaller transmission ranges (say, $r = 25 \sim 50$), we have 'noisy' measurement values as the number of successfully delivered message is small in this range (see Figure 3(a)). For larger transmission range with reasonable message delivery ratio, we again note that similar ordering relationship with respect to the degree of diffusive behavior ($\mu$) holds in general.

In addition to the impact of diffusive behavior on routing performance, we point out again that Figures 2 and 3 together indicate the importance of the metric 'the number of new contacts' especially for DTN routing protocols. Note that, in order to make a successful message delivery upon encounter, the other node upon encounter should be either (i) a new node or (ii) one of the previously-encountered nodes but now with different set of messages in its buffer. Our simulation results in Figures 2 and 3 show that the case (i) plays an important role and the number of new contacts is very effective metric in measuring routing protocol performance.* We expect that our metric based on new contacts is more relevant for other types of DTN routing protocols such as spray and wait [14], where message delivery/transfer among nodes are based on contact events.

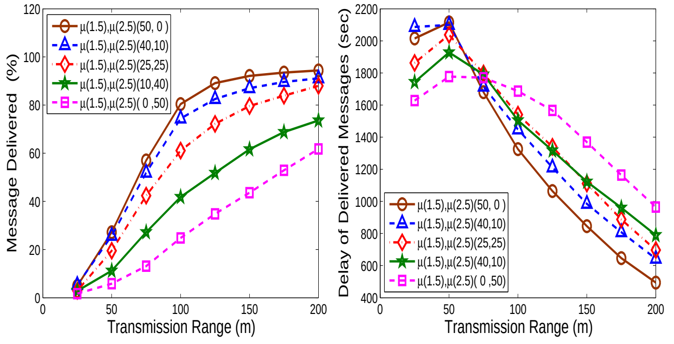


(a) The number of new contacts (b) New contacts with time $t$



(c) The total number of contacts (d) The total contact duration

Fig. 4. Impact of diffusive properties on contact-based metrics under a heterogenous mix of mobility models. Mobile nodes following Lévy walk model with $\mu = 1.5$ and that with $\mu = 2.5$ coexist. We vary the fraction of nodes following Lévy walk model with $\mu = 1.5$ from 0 to 50, while keeping the total number of nodes the same (50 total). For example, legend "$\mu(1.5)$, $\mu(2.5)$(40,10)" means that there are 40 nodes following Lévy walk with $\mu = 1.5$ and 10 nodes with $\mu = 2.5$.



(a) Message Delivery Ratio (b) Delay of Delivered Messages

Fig. 5. Impact of diffusive properties on the performance of epidemic routing under a heterogenous mix of mobility models.

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*This is analogous to epidemic process of diseases in which it takes very long to recover once gets infected (takes long to meet other nodes to get/dump new messages). Thus, most successful message transfer (infection) would take place when they meet for the first time.

### B. Scenarios with Heterogenous Mobility Models

In this section, we consider a scenario in which different mobile nodes may follow different mobility patterns (with different diffusive behaviors). This type of scenario may find some application where mobility pattern of some fraction of mobile nodes are controllable (e.g., data MULE [11]). Specifically, in such a situation, one first needs to specify what type of mobility models the data MULEs should follow for optimal performance, in the presence of other 'usual' (uncontrollable) mobile nodes that are already following certain mobility patterns.

In our scenario, we have total $50$ mobile nodes with two different mobility models. One group of nodes follow Lévy walk mobility model with $\mu = 1.5$, while the rest of them follow that with $\mu = 2.5$. We gradually change the fraction of the first group of nodes from 0 to 50, to see the effect of different mix of mobility patterns on contact-based metrics as well as the two performance metrics for epidemic routing protocol.

Figures 4 and 5 show how contact-based metrics and the performance of epidemic routing are affected when we change the fraction of mobile nodes of two different models. When we increase the fraction of higher diffusive nodes (more nodes follow Lévy walk model with $\mu = 1.5$), the overall diffusive nature as a whole from total of 50 nodes becomes stronger, and as Figures 4(a) and (b) show, this leads to larger number of new contacts and the faster increase of the number of new contacts with time $t$. In the epidemic routing performance evaluation, this tendency still holds. When there are more nodes with higher diffusive properties, message delivery ratio increases while the delay of delivered messages decreases.

## V. SUMMARY AND CONCLUSION

In this paper, we have investigated the impact of different degrees of super-diffusive behavior of mobile nodes that were previously found in real mobility traces on the routing protocol performance in DTN. Our findings in this paper can be summarized as follows: (i) Super-diffusive property in mobility patterns makes significant impact on epidemic routing protocol performance. In particular, we have found that routing performance generally improves as the degree of diffusive behaviors increases. (ii) In order to correctly capture the dependency on the diffusive behaviors, we propose to use the number of new contacts as a key metric that is in direct ordering relationship with message delivery ratio and delay. Our study also indicates that the traditional contact based metrics that do not distinguish old and new contacts are unable to predict performance difference induced by different diffusive mobility patterns. The main intuition behind our findings is our observation that more diffusive mobility patterns tend to promote new contacts among nodes. Our finding in this paper also suggest that the diffusive behavior of mobile nodes should be correctly taken into account for the design and the performance evaluation of routing protocols, since otherwise the design guidelines from traditional mobility models (Brownian motion or RWP) could be either overly pessimistic or optimistic.

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