# DTN Routing Strategies using Optimal Search Patterns

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## ABSTRACT

Biologists have long shown that the mobility patterns of many foraging animals and insects are similar to Levy walks and Levy walks are an optimal search strategy when target objects (i.e., food sources) are sparse and their locations are not known in advance. In this paper, we apply Levy walk patterns to routing in delay tolerant networks (DTN). In DTNs, message forwarding nodes often do not have full information about the whereabout of message destinations. Using the optimality property of Levy walks, we devise two styles of routing strategies. One is an active strategy using message ferries (MF) where the movement of MFs can be controlled to have a Levy walk pattern in order for them to maximize the opportunity of meeting the destinations and the other is a passive strategy in which the movement of nodes cannot be controlled, but messages are forwarded in such a manner that their forwarding patterns mimic the Levy walk patterns. We show through simulation that (1) both strategies are very effective when knowledge about destinations (i.e., contact history, trajectory or locations of destinations) is highly limited and (2) they complement existing utility-based routing which excels when such knowledge is available.

## Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless Communication

## General Terms

Algorithms, Performance

## Keywords

Mobility model, delay tolerant networks, routing performance

## 1. INTRODUCTION

Challenged networks [5] are defined to be a type of networks that violates one or more of the common assumptions explicitly or implicitly made. Examples of these assumptions are that an end-to-end path should exist between a source and its destination or the maximum round-trip time between node pairs in a network should be reasonably small. But in some mobile networks these assumptions may not valid any more. To overcome these extreme conditions, delay tolerant networking (DTN) is arisen as a promising solution. In sparse ad-hoc networks where the node density is not high enough to establish end to end links, the messages are stored in nodes and forwarded through intermittent contacts established by node mobility.

In disconnection-prone networks, routing is a key networking issue [17]. Recently, various DTN routing schemes have been proposed. These schemes are classified as *passive* or *active*. In passive schemes, the movement of nodes cannot be controlled and messages are forwarded or replicated to nodes most likely to meet the destination. This likelihoodness is evaluated based on past history of contacts or prior knowledge of schedules. Active schemes utilize a set of special mobile nodes called *message ferries* acting as message carriers or "postmen". The mobility of MFs can be controlled to maximize the chance of message delivery in sparse networks.

Routing in DTNs resembles "searching" in mother nature. In active routing, MFs are searching for destinations and in passive routing, messages are searching for destinations as they are forwarded to directions with high chances of meeting the destinations. The optimal searching algorithms are given much attention in biology, especially in the studies of animal foraging [13][24][23] or mate-searching behaviors of butterflies [14]. Levy walks (LW) are known to show optimal searching efficiency for sparsely and randomly distributed targets [24]. They are characterized by a power law distribution of flights which are defined to be trip distances that nodes travel without making any directional changes or pauses. Intuitively, LW consists of many short flights with occasional long flights. These LW patterns are found in albatrosses [23], spider monkeys [13], jackals [2], and in visually cued mate locating behaviors of butterflies [14].

In this paper, we apply the LW patterns to DTN routing. We propose two new DTN routing algorithms for both active and passive schemes. The passive one is called *Scale Free Routing (SFR)*. It utilizes both flight distributions and utility information [7] in the networks. The other one is an active strategy where MFs perform Levy walks to maximize the message delivery ratios and delays. We report a preliminary performance study of these schemes. They show high potential to be effective routing strategies for DTNs.


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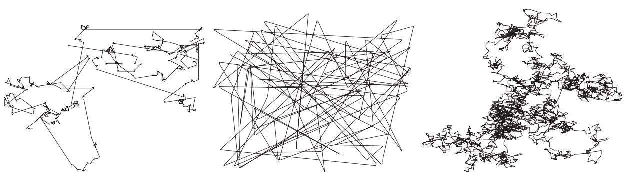


(a) (b) (c)

**Figure 1: Sample traces of (a) Levy walks, (b) RWP and (c) BM**

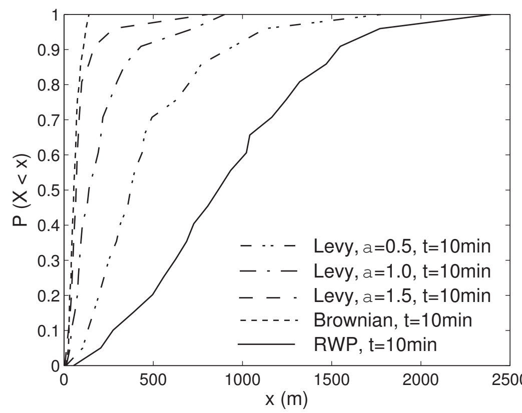



**Figure 2: The CDF of user displacements from its initial position in a fixed travel time. RWP is most diffusive while BM is least diffusive. The diffusion rates of Levy walk are in-between. The values in the parentheses represent the Levy exponent for flight length.**

This paper is organized as follows. Section 2 contains background information about Levy walks. Section 3 presents the passive scheme and Section 4 discusses the active scheme. Section 5 presents related work on existing DTN routing algorithms. Section 6 concludes the paper.

## 2. LEVY WALK MOBILITY MODEL

A variety of mobility models have been proposed [4]. Random Way Point (RWP) and Brownian Motion (BM) are well known models. These models are simple and mathematically tractable. However, there has been little statistical validation of such models for accuracy in describing human mobility. Recently we proposed a Levy walk mobility model [16][15] called *Truncated Levy Walks* (TLW) in which flight length and pause time distributions follow truncated power laws. We show based on the analysis of GPS recorded human walk traces that these heavy tailed flight length and pause time distribution in TLW statistically resembles human mobility. $p(l)$ and $\psi(t)$ represent flight and pause time probability density distributions in TLW, respectively. Then their asymptotic behavior can be expressed as follows [10].

$$p(l) \sim |l|^{-(1+\alpha)} \tag{1}$$

$$\psi(t) \sim t^{-(1+\beta)}, \text{where t} > 0 \tag{2}$$

$\alpha$ and $\beta$ have a value between 0 and 2. When $\alpha$ (or $\beta$) is 2, $p(l)$ (or $\psi(t)$) becomes a Gaussian distribution. When $\alpha \geq 2$, the model becomes BM due to the central limit theorem [18]. Flights and pause times cannot exceed certain values, $f_{max}$ and $p_{max}$, respectively. Fig. 1 illustrates sample traces of LW, RWP and BM.

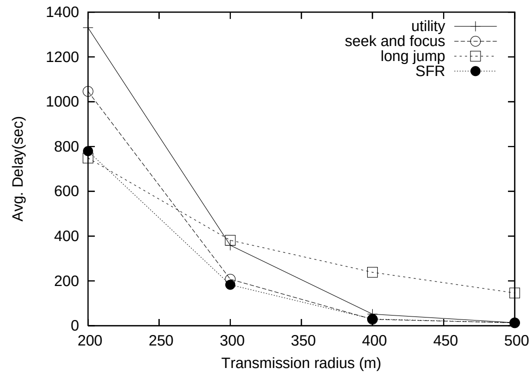
One of the important characteristics of Levy walks is its high diffusivity [16][15]. Diffusivity can be defined to be the variance of the displacement between the current position at time $t$ and a previous position at time $t_0$. Fig.2 shows the amount of displacement for various mobility models plotted in CDF. In this simulation, all mobility models use the same velocity and pause time distributions, and traces are taken from the same area. It can be shown that the difference in displacement patterns comes from the difference in their flight distributions. In Fig.2 we can see that RWP is most diffusive while BM is least diffusive, and Levy walk model is in-between.

Throughout this paper, we use the TLW model for simulating different DTN environments. For comparison, we use RWP and BM as well.

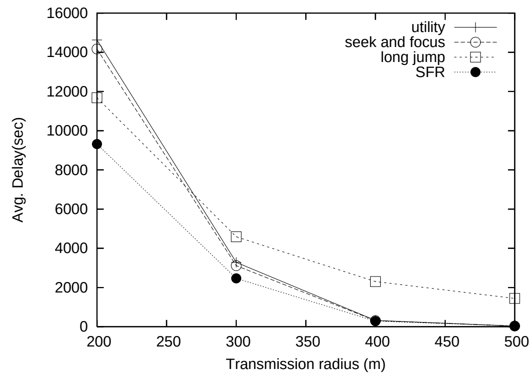
## 3. SCALE-FREE ROUTING

We consider a network with no special purpose node where each node can participate in routing as relays. The movement of nodes cannot be controlled, so that we call this kind of routings as passive schemes. We examine various single-copy DTN routing schemes in which a single copy of each message exists in the network at any time and the delivery consists of multiple message forwarding. Replication schemes are not considered and are left as a future study. In single-copy routing, the decision when and to which node messages are forwarded is an important performance determinant. Single-copy routing is an important building block for multi-copy (or replication) schemes. We propose a new hybrid scheme that maximally exploits the mobility of relay nodes by selecting as relays the nodes with the highest probability to move farthest from the current location when information about destinations is limited. We call such nodes *ballistic nodes*. Intuitively, ballistic nodes are the highest diffusivity and thus visit many new locations. This increases the chance to meet destinations or other relay nodes that have higher chance of meeting them.

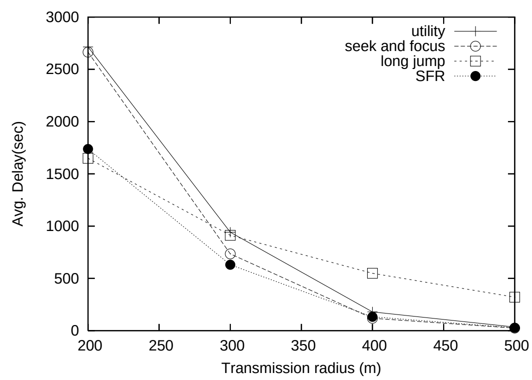
Most existing DTN routing algorithms [25] are designed to work in an environment where at least some amount of information about destination nodes is present. This information typically comes in the forms of recent contact history or prior knowledge on the mobility schedules of destination nodes. Based on this information locally available through communication with neighboring nodes, the algorithms use *gradient schemes* to forward messages to other nodes in such a manner that maximize the value of this information, called *utility*. However, their behaviors are unpredictable when local utility is very low. In fact, it is known [20] that in such environments, gradient schemes lead to local optima and incur much higher delay than simple random forwarding where relays are picked randomly. SFR improves on random forwarding. It works as follows. If utility is lower than certain threshold, SFR chooses ballistic nodes as relays until nodes move into an area where utility is high. Otherwise, it switches to gradient schemes. The definition of utility can vary depending on gradient schemes and SFR can be applied to any gradient schemes. SFR is similar to Seek and Focus [20] in that it uses random forwarding under low utility and




(a) RWP model




(b) TLW model




(c) Heterogeneous models

**Figure 3: Average message delivery delays under various DTN routing schemes. Last encounter times are used as utility. We assume that all nodes know their current waypoints.**

utility-based gradient routing under high utility. SFR differs only in the way that the most ballistic node is chosen as a relay while in Seek and Focus the next relays are chosen randomly.

Knowing the flight length of each mobile node is a strong assumption. Making a forwarding decision with aim to send a message far distance away from the current area can be deduced from mobility information. The following information can be used.

1. Waypoint: A node with mission information can tell their next destination; with GPS, we can deduce the remaining distance to the destination. A node with the longest remaining distance is chosen as a relay.

2. Trajectory: Each node estimates its radio covered area in last $N$ minutes. A node with the largest covered area can be considered to have the longest flight. It is chosen as a relay.

3. Meeting History: If GPS is not available, the number of new neighbors that the node has met recently can be recorded to estimate the amount of mobility of that node. A node with the largest number of new neighbors is chosen as a relay.

4. Position: If the current position, velocity, and direction of nodes are available, the next positions of the neighbor nodes at $T$ seconds later can be estimated. A node with the largest estimated value in the same direction as the current node is chosen as a relay.

Note that these clues for ballistic movements are not related to message destinations, but rather related to the mobility patterns of nodes.

To measure the potential of SFR, we first run simulation using a strong assumption that each node knows their next destination and remaining distance to the destinations of their waypoints. Simulation setups are as follows. 100 nodes are uniformly spread in 4km by 4km area with wrapped-boundary. At every 5 seconds, each node transmits a beacon signal to communicate with neighbor nodes. All the nodes move with the speed uniformly chosen from [9m/s, 11m/s]. The minimum flight length is fixed to 10m and maximum is set to the length of a side of simulation area. The utility threshold is set to have same value (500 secs) in both SFR and Seek and Focus. There is no pause time between flights so that all the nodes continuously move. We want to emphasize the effect of flight length distribution in this paper and leave the impact of pause time as future work. Totally 300 messages between random pairs of source and destination are generated and each simulation run is terminated when 200 out of 300 messages are delivered to their destinations. All results represent the averaged delay values over 10 independent simulation runs. The underlying mobility model is varied from RWP, TLW and heterogeneous model where the mobility of each node is randomly selected among BM, RWP and TLW. For TLW, we use $\alpha = 1$.

Fig. 3 shows the routing delays under various forwarding algorithms and mobility models. The transmission range is a parameter to represent the degree of node density. In this experiment, we use the *last encounter times* of nodes as utility where each node records the last encounter times with each neighbor and the nodes with the most recent encounter times have the highest utility. *Long-jump routing* chooses always more ballistic nodes in the neighbors as relays. *Utility routing* uses a gradient scheme based on utility (e.g., last encounter times). All figures show a similar trend irrespective of mobility models. Under low density, the long-jump routing and SFR have smaller delivery delays compared to utility and seek and focus. Since under low density, utility is typically low, SFR uses ballistic nodes as relays in the same way as long-jump routing. However, long-jump routing suffers from much higher delays when the node density is getting higher. In contrast, SFR achieves similar performance as utility routing. Under high node density, because of high connectivity, nodes tend to have high utility. Thus,

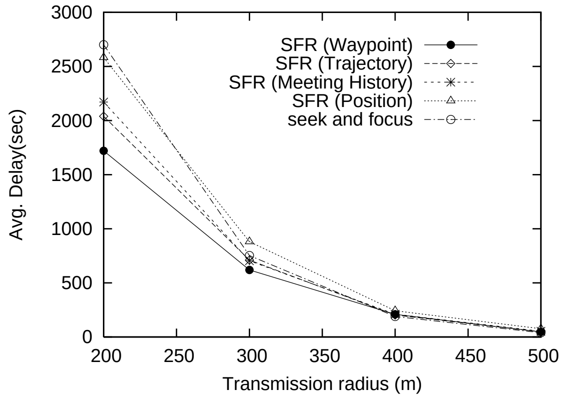



**Figure 4: Average message delivery delays of SFR with different relay selection schemes. It is tested under heterogeneous mobility. Each SFR scheme chooses a relay node based on waypoint, trajectory, meeting history and position information.**

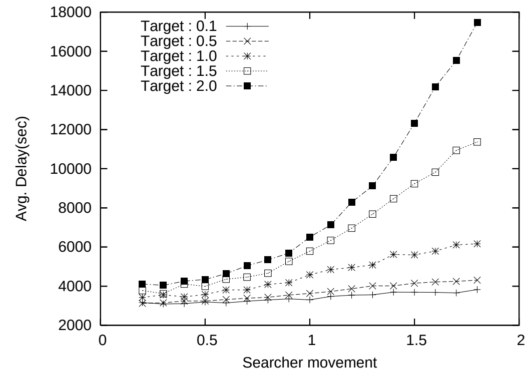



**Figure 5: Average message deliver delays when using one message ferry with a fixed transmission range. The mobility of target nodes and MF is controlled by TLW with different $\alpha$. As we vary $\alpha$ of MF (X axis) and target nodes, we measure their message delays. For instance, Target:0.1 denotes that target nodes move according to TLW with $\alpha = 0.1$.**

SFR works like utility routing. Seek-and-focus uses random forwarding when utility is low. Thus, its performance is much lower than long-jump routing and SFR under low density, especially when TLW and heterogeneous mobility are used. Under RWP, its performance gets improved (but still far less than SFR) because all nodes in RWP move in a rather ballistic manner and thus randomly chosen nodes are likely making long flights.

Fig. 4 shows the routing delays when we relax our assumption about the knowledge of waypoints. The four schemes of choosing a ballistic relay are used. Compared with the results in Fig. 3 (c) we can see that SFR with trajectory and meeting history still outperforms other existing schemes such as utility and seek and focus routing, especially under low node density. It shows that position information is not useful for choosing ballistic relays. This shows that SFR can be practically adapted while achieving better performance than existing schemes.

# 4. LEVY MESSAGE FERRIES

In this section, we investigate the DTN routing performance when message ferries are introduced and their mobility patterns follow TLW. To focus on the effect of the mobility patterns of message ferries, we assume that messages are delivered only by one MF node and other nodes just generate or receive messages.

In each simulation run, all nodes except MF (we say *target nodes*) move according to TWL with $\alpha$. We again assume that nodes do not make pauses. For different runs, we vary $\alpha$ to see the effect of underlying mobility on the performance. MF also uses TLW but uses different values of $\alpha$. The different values of $\alpha$ represent the different diffusivity of node mobility. As $\alpha$ becomes smaller, the occurrences of long flights get more. It induces higher diffusivity. If the parameter is larger than 2, the long flight probability diminishes rapidly and the motion approaches to BM. In this section, we study the relation between the mobility patterns of MF and target nodes. Through simulation, we identify the conditions in which DTN routing delays are minimized.

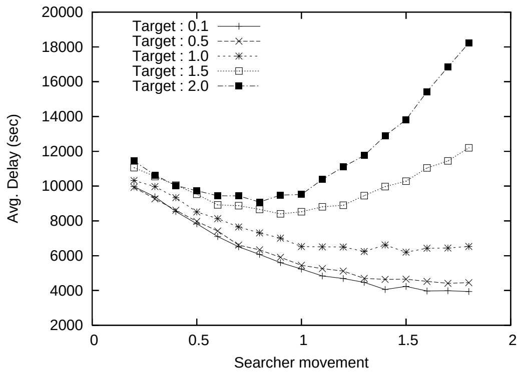
Simulation setups are same as in Fig. 3. One MF is moving inside the area to deliver messages. At every 2 seconds, MF tries to communicate with its neighbor nodes.

## 4.1 Fixed Transmission Range

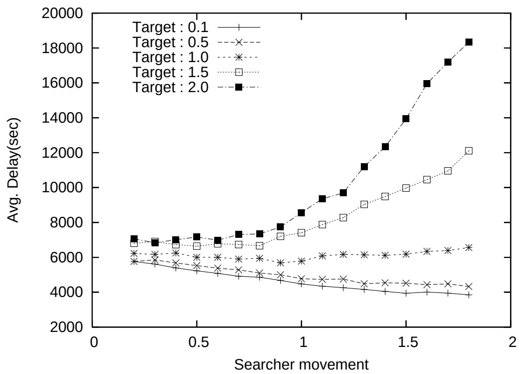
First, we examine DTN routing under an assumption that the transmission ranges of all nodes are constant irrespective of their moving speed. This assumption is widely adopted. Fig.5 shows the average delays under different movement of MF and target nodes. Regardless of the diffusivity of the target nodes, the ballistic movement of the MF shows smaller delays. An MF with high diffusivity increases chances to meet other nodes and deliver messages. The figure also shows that the average delays of high diffusive nodes are less affected by the MF mobility in contrast to the low diffusive nodes. If both target nodes and MF move according to BM, the meeting probability is far reduced. This result indicates the effectiveness of previously proposed equipments such as throwboxes[26]. Throwboxes are designed as relay nodes to facilitate DTN routings and those are fixed at some locations (zero diffusivity). When the locations or mobility schedules of destinations are not known, throwboxes may be an effective device only if used with highly mobile target nodes, but will poorly perform in a condition that the nodes movements are not so diffusive.

## 4.2 Varying Transmission Range

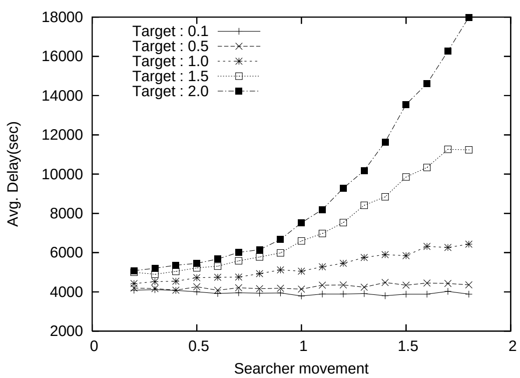
In this section we relax the assumption on constant transmission ranges. In reality, when nodes move faster their transmission ranges get smaller [11]. As nodes move in varying speeds, this consideration of varying ranges is important. For instance, in [16] it is shown that the speed of humans has high correlation with flight lengths. That is, velocity increases as flight lengths increase. We say that a node is in the *relocation phase* when it has a waypoint longer than 100m; otherwise, it is in the *searching phase*. We denote by $p$ the degree by which transmission range gets reduced when a node is in the relocation phase and when in the searching phase. We vary $p$ from 0.25 to 0.75 (with $p = 0.25$, during relocation, the transmission range of nodes gets reduced by 75%).




(a) range p=0.25




(b) range p=0.50




(c) range p=0.75

**Figure 6: Average message delivery delays when using one message ferry. The mobility of target nodes and MF is controlled by TLW with different $\alpha$. As we vary $\alpha$ of MF (X axis) and target nodes, we measure their message delays. For instance, Target:0.1 denotes that target nodes move according to TLW with $\alpha = 0.1$.**

Fig. 6 shows the average message delivery delays under various $p$ values. It indicates that depending on the mobility patterns of target nodes, MF needs to vary its mobility patterns to minimize the message delivery delays. For instance, in $p = 0.25$, BM targets ($\alpha = 2.0$) require MF to move with $\alpha = 0.8$ to minimize the delays, and ballistic targets ($\alpha = 0.1$) requires MF to have very little motions as BM. This result is due to the fact that ballistic motion loses its merit because of the far reduced range and that BM is inherently less diffusive in spite of maintaining the maximum range. Actually, the DTN routing delays of ballistic targets are not much dependent on the MF mobility types. Our study indicates that with varying transmission ranges, ballistic MF is not necessarily desirable for reducing delays. In fact, the more the target nodes are mobile, the less mobile MF should be to achieve the best performance, suggesting that adjusting the statistical mobility patterns of MF according to the statistical mobility patterns of target nodes yield good performance.

# 5. RELATED WORK

Many different routing protocols in DTNs have been developed [25] [8]. The routing algorithms can be categorized by whether they use specialized relay nodes or whether they allow concurrent multiple copies of messages exist. Message ferries [21] and throwboxes [26] are typical examples of specialized nodes. Since missed contact opportunities among nodes severely decrease performance and increase delays, the use of these special purpose relay nodes help improve the performance of DTN by increasing the probability of contacts among nodes. Both message ferries and throwboxes can act as relays, but the main difference between them is that throwboxes are stationary while message ferries are moving. So for message ferries the main challenge is the design of route to achieve high chance of meeting other nodes.

Epidemic routing [22], *Spray and Wait* [19] and RAPID [3] are examples of multi-copy routing. Epidemic routing is like flooding the message throughout the network. In this scheme, every node sends out all its messages to its neighbors. Although this scheme guarantees to find the shortest path when no contention exists, it extremely wastes resources such as bandwidth. In Spray and Wait routing, initially messages are copied to $L$ relays and if the destination is not found in a certain period of time the relays nodes wait until they meet the destination. RAPID can maximize the performance of a specific routing metrics intentionally, e.g. average delay, missed deadlines or maximum delay.

All the other routing schemes which use single copy without any help from special purpose relay nodes are called single copy routing. Direct transmission, Two hop relay [6], Randomized Routing, Utility based routing [1] [7], Mobispace [9] and Seek and Focus [20] fall into this category. These algorithms utilize routing metrics such as last encounter time but they depend on random or direct forwarding especially when the knowledge on the destination or network topology is limited. None of these exploit the advantage of high diffusive node.

# 6. CONLCUSION

Various routing algorithms in DTN environments have been proposed but none of the existing algorithms exploit the advantages obtained from the diffusivity or mobility patterns of mobile nodes. In this paper, we have applied Levy walk patterns to DTN routing strategies and examined their performance. First, in passive single copy routing, we show that ballistic nodes can be effective relays to reduce the overall delivery delays. Ballistic nodes mimic long flights in Levy walks while utility-based gradient routing can be viewed as short flights. The mobile nodes with those patterns have great advantages in reducing routing delays since high diffusivity by long jumps increases contact probabilities between relays and destination nodes. For active routing scheme using message ferries, we also utilize optimal search patterns of Levy walk. It is known that Levy walk patterns result in optimal search for scarce and randomly distributed targets. We demonstrate that with more realistic assumptions on the wireless transmission ranges of mobile devices, our Levy message ferry movement patterns ($1 < \alpha < 2$) show the best performance.

We find that utilizing the mobility patterns of mobile nodes can give great advantage in delivering messages in DTNs. Our work is an important step to improve application performance in DTN environments. Our SFR can be easily extended to replication based multi-copy routing algorithms. We leave that as future work. The Levy walk search patterns can also be used for other applications such as content distribution (e.g., [12]) in DTN environments.

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